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ON-BOARD VEHICLE SENSOR TECHNOLOGY
Volume II Technical Report

Contract No. DOT-HS-5-01178
July 1977
Final Report

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16. Abstract

Forty three areas were identified in the brake, steering, suspension, tire, lighting and signalling systems where safety or inspection benefits might be obtained through the application of on-board vehicle sensors utilizing either on-board or off-board readout. These areas were screened against a variety of criteria, the most important being their potential for accident reduction as determined in the Indiana Tri-Level Studies in Accident Causation. Eleven areas were judged to warrant detailed evaluation of implementation considerations.

These eleven candidate areas were then subjected to further analysis including identification of: currently available hardware, existing techniques for sensor application, conceptual devices where hardware does not now exist, and improvements possible in existing devices. In addition, a cost benefit analysis was performed for each candidate area, utilizing estimates of sensor life-cycle cost and benefit, including both safety and other impacts. These results are preliminary in nature, due to the weakness of the data bases in all important areas. Limited consideration was also given to alternative countermeasures in each area. Four candidate areas are judged to offer the potential of a favorable benefit/cost ratio. These are brake performance, tire tread depth, brake lights and brake friction material.

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METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

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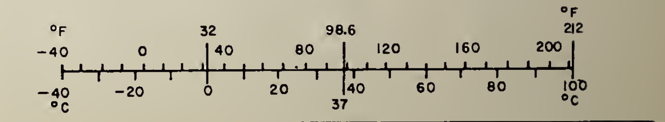
*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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1.0 INTRODUCTION

The On-Board Vehicle Sensor Technology Program has been a research effort, assessing the state-of-the-art and potential areas for future development of on-board vehicle sensors and deriving their applicability to passenger car brake, steering, suspension, tire, lighting and signalling systems.

In its introduction to the statement of work, NHTSA states:

> "The National Highway Traffic Safety Administration (NHTSA) believes that automobiles equipped with on-board vehicle sensors for the continuous and/or periodic monitoring of safety critical systems, subsystems, and components could have a substantial impact on highway safety."

The specific objectives called out in the original statement of work are:

1. Identify candidate subsystems and components in the brake, tire, steering, suspension, lighting and signalling systems from which inspection and safety benefits may be obtained by means of on and off-board sensor techniques.

2. Determine specifically those candidate subsystems and components which require monitoring using on-board vehicle sensors and those requiring only periodic surveillance using off-vehicle equipment in conjunction with an interface device.

3. Develop, validate and recommend optimum on-board sensor systems for both continuous and/or periodic monitoring of safety critical subsystems, and components.

Three individual tasks* have been carried out to fulfill the specific objectives listed above. Task 2 involved determination of where to apply sensors, based on accident data and other sources. It also involved determining whether the readout should be on-board or off-board. Task 3 involved determination of how to provide sensing in the selected areas. Under Task 4, selected sensors from Task 3 were tested and display models were constructed and delivered to NHTSA.

---

*Tasks 2 through 4. Task 1 was the preparation of a plan-of-work and methodology, and is not specifically described in this report.

The relationship between Tasks 2, 3 and 4 is illustrated in Table 1-1. which illustrates a progressive reduction in the number of on-board sensor concepts considered. In Task 2, a list of 48 possible areas for sensor application was reduced to 11 candidate sensors. In Task 3, this list of sensors was evaluated from an applications point of view. Task 4 was originally conceived as involving development of two sensor concepts and the fabrication of working displays for three additional application areas. At NHTSA direction, this task was rescoped to include laboratory demonstration of one sensor concept and the fabrication of static displays for a total of three application areas, and in turn the laboratory demonstration became one of the three displays. It is, however, an active rather than a static display.

TABLE 1—1. TASK SEQUENCE OF ON-BOARD VEHICLE SENSOR TECHNOLOGY PROGRAM

Task	Concepts considered	Areas of activity
2	48 potential areas	Need for sensors Readout mode
3	11 candidate areas	Implementation Practicality Cost/Benefit analysis
4	3 application areas	Two static sensor displays
	1 development area	One laboratory concept demonstration (included in active sensor display)

Also at NHTSA direction, the sensor evaluations performed in Task 3 were rescoped to include a preliminary cost-benefit analysis of the eleven candidate areas for sensor application. This involved an in-depth review of each sensor area - its justification in safety terms, its economic impacts, and its potential relative to alternative measures.

There are many countermeasures available for reducing component failures as a cause of motor vehicle accidents. These include motor vehicle inspection (periodic and random), improved vehicle design, increased law enforcement for visible defects, driver education/public information programs, and the use of on-board vehicle sensors. This program, although directed principally at the on-board vehicle sensors, has required the definition and (preliminary) resolution of several important issues common to the analysis of all vehicle-in-use (VIU) accident countermeasures.

2.0 CANDIDATE AREAS (TASK 2)

Task 2 had two objectives. The first was to identify candidate vehicle subsystems and components in the brake, tire, steering, suspension, signaling and lighting systems that may provide safety and/or inspection benefits through their continuous and/or periodic monitoring. The second was to determine which areas are more suitable for (a) continuous/periodic on-board driver monitoring, and (b) those areas best suited for off-board monitoring when used in conjunction with additional equipment. These objectives were fulfilled through the development and application of a formal evaluation algorithm that included relevant decision criteria for both objectives, as well as structuring the evaluation to minimize redundant activity.

The determination of candidate areas for sensor application was (by requirements in the Statement of Work (SOW)) based on the following criteria:

- Historical vehicle accident data
- Performance degradation data
- Failure data
- Subsystem/component fault frequencies
- Motor vehicle inspection problems
- Inspection data
- Inspection technology

The first four of these relate to whether a safety benefit exists. The latter three relate to whether an inspection benefit is provided. Inspection benefit has been defined as:

1. complementing, automating, or eliminating inspection of components.
2. reducing or eliminating manual inspection.
3. alleviating problems due to subsystem or component inaccessibility, nonvisibility, or system complexity.

Inspection benefits are obtained when off-board readout (through additional interface equipment) is employed. Safety benefits may be derived through either on-board (real-time) readout or through vehicle inspection. For each candidate sensor, the determination of the appropriate readout mode was based on criteria provided in the SOW:

- component criticality
- driver display format
- probability of driver use
- inspection system requirements.

In general, components monitored by a sensor with on-board readout capability can also utilize the same sensor in an off-board readout mode. In cases where both the costs and benefits of the sensing element vary as a function of the method of implementation, certain sensors were placed on both candidate lists at this stage of the program. Such, for example, has been done in the case of two different types of brake wear indicators; one suited for on-board readout, the other an inexpensive sensor whose use would simplify the inspection process. The relative merits of these two devices has been evaluated as part of the Task 3 (Sensor Identification) effort. At the Task 3 level, the decision as to whether the brake wear indicator or any sensor should be implemented in an on-board or off-board readout mode has been based on the relative costs of the two devices and the benefits of the two approaches.

Although the general criteria to be applied in evaluating sensor candidate areas were specified by the SOW, the details of how, and in what sequence, these criteria were applied were left for resolution by the contractor. After preliminary consideration of the data sources available, and discussions with NHTSA, an evaluation algorithm was developed to formalize the process of candidate area identification.

2.1 METHODOLOGY

The algorithm shown in Figure 2-1 outlines the method used to apply evaluation criteria to the list of potential areas. This algorithm specifies the content and sequence of tests to be applied in each measurement area. The details for each criterion are as follows:

> Criterion 1 - Can the safety benefit be documented in accident records? Components whose failure can be cited as accident causes in such reports as the Indiana study should be the least controversial in terms of their safety criticality. Although allowances must be made for the limitations of sample size and the sample typicality in terms of drivers, vehicles, and road conditions, indictment of a component in more than one-half percent of the accidents considered should be prima facie evidence for further consideration.

The selection of one-half percent is a reasonable starting point on the basis of the limited number of cases available from the Indiana study. This level of acceptance has been reviewed after a preliminary assessment of the case studies and found acceptable in terms of the number of sensing systems identified. It should be noted that the original screening is designed to pass the maximum number of components because more restrictive tests can be applied at a later stage.

> Criterion 2 - Does component degradation significantly affect limit performance? This represents a criterion which can be rigorously applied, in view of a number of NHTSA studies on brake system degradation, shock absorber, steering, ball joints, etc. This criterion is intended to identify degradation modes which are too subtle to be directly implicated in accident data. In general, the data sources which have been used in applying this criterion are laboratory studies of vehicle driver performance, rather than accident statistics. There is, however, a caveat. A degradation in limit performance capability has been regarded as significant only if the use of that limit performance capability can be documented in the prevention of accidents. For example, a reduction in brake maximum deceleration capability from 0.90 to 0.89 g has not been treated as significant, because the effect of the missing 0.01 g cannot be measured.

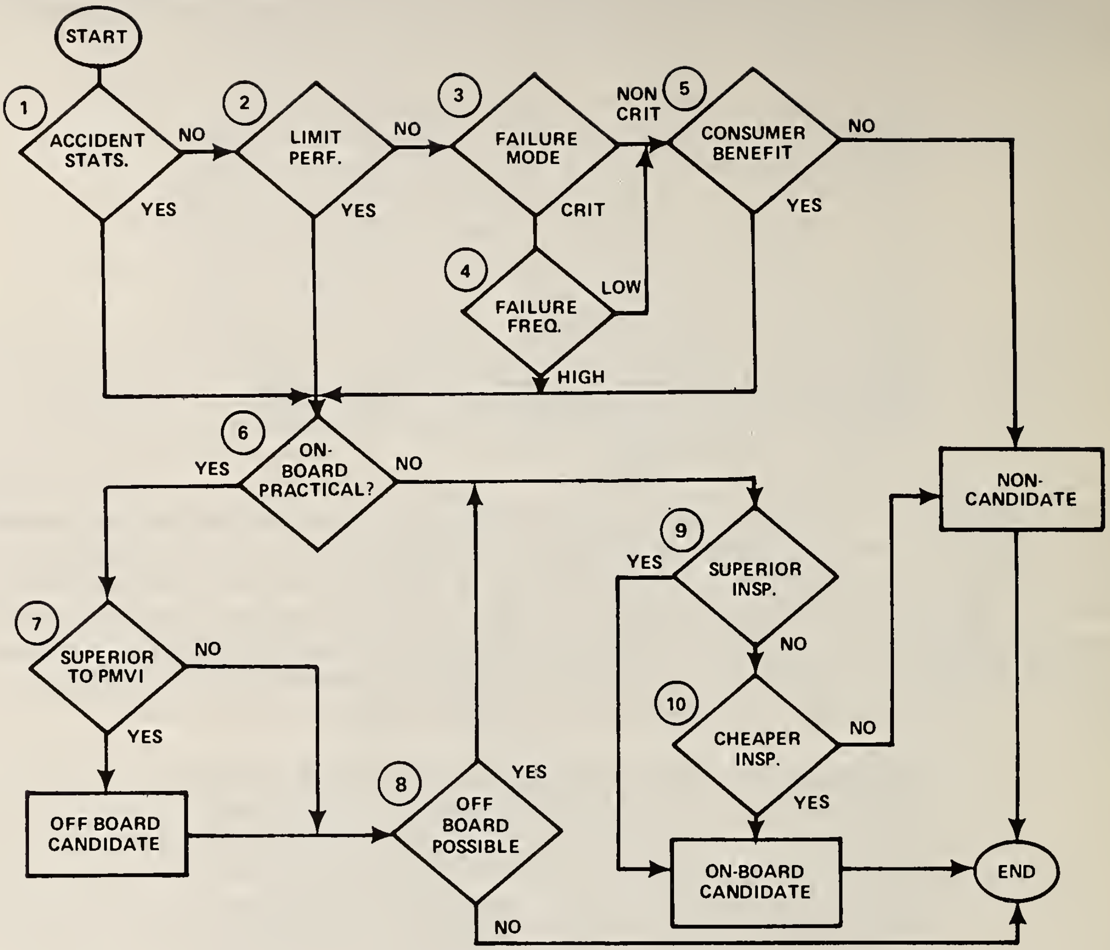

Figure 2–1 ALGORITHM OF TEST CRITERIA FOR ESTABLISHING SENSOR CANDIDACY

> Criterion 3 - Does component failure create an immediate safety hazard? Application of this criterion involves the use of fault free or failure mode analysis. For example, the loss of a wheel constitutes an immediate safety hazard. Therefore, anything which might permit a wheel to fall off would constitute a candidate sensor area within this criterion. Consideration of whether the failure mode occurs frequently is a separate criterion.

Conceptually, selection Criteria 2 and 3 (limit performance and failure mode) are non-interactive. Limit performance degradation is conceived as a phenomenon which becomes manifest in an abnormal driving situation. The failure mode criterion applies to areas or components which create an abnormal situation. There may, in fact, be an interaction between Criterion 1 and Criteria 2 or 3. This is accommodated in the definitions of limit performance degradation and critical failure mode. Existence of case studies documenting the involvement of specific defects at a level below the threshold required for selection by Criterion 1 can subsequently be taken as evidence of either limit performance degradation or a critical failure mode in subsequent tests.

> Criterion 4 - Does the component fail frequently? For components whose failure constitutes an immediate safety hazard, but does not fail sufficiently frequently to be detected by accident investigations such as the Indiana study, Avco has sought other sources of failure data, such as repair records, to determine whether the postulated failure mode occurs often enough to be of concern.
>
> Criterion 5 - Does sensing of the component offer a consumer benefit? Perhaps the best example is thickness of brake friction material. It has been argued that the principal benefit of sensors for lining/pad thickness is to alert the motorist to the need for replacement before damage occurs to the drums or discs. If this is true, and if this benefit is truly significant, this will be regarded as sufficient justification for further consideration.

If a sensor area has failed to be established as one to be considered a candidate in each of the first 5 test criteria, it is designated a non-candidate, ending its consideration in this study, as indicated in

Figure 2-1. Sensor areas that are still in contention after the first five tests are further screened in Tests 6 through 10, which further establish the sensors as on-board or off-board candidates, or possibly non-candidates based on lack of any payoff for practicable off-board sensors. Criteria for Tests 6 through 10 follow.

> Criterion 6 - Is it practical to provide real time readout to the driver? If so, the potential exists for an immediately recognizable safety benefit in the form of more timely diagnosis.
>
> Criterion 7 - Will the safety benefit of sensing be significant relative to PMVI? The following are among the considerations that will be included in this evaluation: probability of failure, failure mode, probability of unaided diagnosis, and probability of correct driver response. Avco has developed a mathematical model of owner behavior and its relationship to PMVI which, for a particular failure mode (random failure), may be useful in identifying those potential areas which would provide the greatest benefit through real time readout. Basically, the test to be applied concerns the ratio of reject rates with and without PMVI, or alternatively with PMVI carried out at two different inspection frequencies. If this ratio is near unity, and if the inspection system error rate is acceptably low, one possible conclusion might be that the inspection interval is too long to have any impact on the outage rate. Therefore, an on-board sensor that corresponds to the very frequent inspection limit might provide increased benefits. However, Avco's model also predicts that reject rate ratios near unity also correspond to cases in which the probability is high that the owner will detect and correct the deficiency himself. The appropriate conclusion in this case may be just opposite to that noted above -- the deficient item is so visible that an on-board sensor is not required. Additional tests can be applied to resolve this ambiguity. In those cases where PMVI does make a large change in the reject rate, it would seem that more frequent inspection could still further reduce the defect probability. The tradeoff in such cases then becomes a cost question, one to be answered in Task 3.

Criterion 8 - Is off-board readout possible? In general, areas which can be monitored by on-board readout, can also be monitored off-board. Exceptions occur for conditions which develop as a result of vehicle use, but which might not exist when the vehicle is subjected to inspection. Examples such as brake or bearing overheating would fall into this category. The purpose of this criterion is simply to exclude areas which must be monitored by on-board readout from consideration as off-board candidates.

Criterion 9 - Would the on-board sensor provide a superior inspection? A superior inspection, for purposes of this evaluation, is defined as one offering: (a) reduced subjectivity on the part of the inspector, or (b) a reduced error rate (where the term error refers either to the identification of a non-existent defect or failure to identify a defect actually present), or (c) an improved diagnostic content. Those feasible sensor areas that provide a superior inspection would be classified as candidate areas without regard to cost. Avco believes that manual inspections that do not involve subjective criteria, and those that do not represent an error problem, should be eliminated only when their elimination can be justified in terms of the cost to inspect.

Criterion 10 - Would the on-board sensor and associated readout devices cost significantly more than present inspection techniques? This criterion would be applied to proposed areas where an existing procedure is not demonstrably inferior (Criterion 9). If the proposed sensor can eliminate problems associated with subsystem or component inaccessibility or non-visibility, or system complexity at a reduced inspection cost, it would be considered a candidate area. The cost estimates for the on-board sensors will be deliberately optimistic to permit inclusion of as many candidates as possible. Avco is evaluating the cost of existing inspection procedures through its involvement in the Title III demonstration projects and its association with the District of Columbia Diagnostic Research Lane.

We have also incorporated the findings of the Static Brake Program, a current NHTSA contract directed toward investigating ways of reducing the time (man minutes), and, hence, costs required to inspect brake components.

2.2 APPLICATION OF METHODOLOGY

Having a suitable algorithm, the performance of Task 2 is based on formulating the list of potential candidate areas for sensor application and carrying out the tests required.

An initial list of potential candidate areas was established based on Avco's initial understanding of vehicle defects and accident causation and supported by conversations with Avco personnel working in related areas, NHTSA personnel, and Avco consultants. In preparing this list Avco identified as many ideas as possible, without regard to practicality. During the course of the accident case reviews, a number of sensor areas were added to the original list of potential candidates. In the interest of providing a systematic method of identifying potential sensor areas, sensors on the list originally developed were numbered 1 through 43. Additional candidate sensors introduced after the original list was compiled, have been inserted in the list at the appropriate place with an alphabetical suffix (e.g., A, B, etc.) on the preceding 2 digit number. The revised list of 48 candidate sensors is presented in Table 2-1.

The remainder of this section is organized according to the specific criteria listed in the evaluation algorithm, with discussion and results relating to each criterion provided in subsections 2.2.1 through 2.2.6.

2.2.1 Accident Statistics

For each of the potential candidate areas for sensor application, the first test is whether the sensor can be justified on the basis of existing accident data. This test has also developed as the most important criterion for sensor evaluation, and considerable effort was expended in evaluating the data source selected. Because this subsection represents such a substantial portion of the area identification activity, it has been further subdivided along the following lines:

- Data Sources
- Methodology for Accident Case Evaluation
- Case-By-Case Evaluation
- Discussion of Results.

TABLE 2–1. POTENTIAL AREAS FOR ON-BOARD OR OFF-BOARD SENSING

Suspension	
1	Wheel Bearing Condition
2	Wheel (Spindle, Steering Knuckle) Integrity (Front only)
3	Ball Joint or King Pin Condition (Front Only)
4	Shock Absorber Condition
5	Spring Condition
6	Control Arms and Stabilizer Bushings Condition
7	Fastener and Bracket Integrity or Condition
8	Wheel Fastener Condition
9	Lubrication Status
Steering	
10	Steering Wheel Play
11	Linkage Integrity/Condition
12	Wheel Alignment Status (Caster, Camber, Toe)
13	Fastener and Bracket Integrity or Condition
14	Lubrication Status
15	Power Steering Fluid Level/Fluid Flow
16	Power Steering Belt Status
16A	Excess Torque
Lighting	
17	Headlight Aim
18	Headlight and Running Light Status (Intensity)
19	Lens Integrity
20	Status of Other Lights
Brakes	
21	Pad and Lining Wear
22	Reservoir Level
23	Brake Fluid Leak
23A	Grease Leak
Brakes (Concl'd)	
24	Drum/Rotor Integrity/Strength
25	Flex-Line/Rigid Line Integrity
26	Brake Fluid Contamination (Water)
27	Drum Brake Adjustment Status
28	Performance
29	Rotor/Drum Temperature
29A	Pedal Overtravel
29B	Mechanical Operation
Signaling Systems	
	Turn Indicators and 4-Way Flasher
30	Light Status (Intensity)
31	Flash Rate
32	Cancellation Status
33	Circuit Element Status
34	Lens Integrity
	Horn
35	One Horn Failure in Dual Horn System
36	Circuit Element Status
	Brake Lights
37	Light Status (Intensity)
38	Lens Integrity
39	Circuit Element Status (Electrical)
Tires	
40	Tire Pressure (under inflated)
40A	Tire Pressure (over inflated)
41	Tire Integrity
42	Tread Depth
43	Wear Pattern

2.2.1.1 Data Sources

NHTSA personnel in the Office of Statistics and Analysis, as well as NHTSA contractors, such as Calspan, (Ref. 1) have recognized that:

1. the data base on accident causation is quite limited (relative to data on accident occurrence).

2. the data base on the role of vehicle defects in accident causation is still more limited.

3. the best piece of work on mechanical defect accident causation has been the Tri-level Accident Investigations conducted by the Institute of Research in Public Safety (IRPS) at Indiana University.

As for other potential sources, such as the on-going NHTSA-sponsored accident investigation projects listed in Table 2-2. Avco was advised (Ref. 2) that these projects have concentrated their efforts on specialized investigations and have not sampled the accident population with the same care as Indiana, nor have they necessarily investigated the accidents sampled for mechanical defects.

TABLE 2–2. DATA SOURCES FOR THE ROLE OF DEFECTS IN ACCIDENT CAUSATION

Source	Comments
Tri-level Accident Investigations, Indiana University	Best source of data.
Other multi-disciplinary studies	Not generally applicable; emphasis on:
Boston	Single vehicle accidents
Baltimore	Fatal accidents only
Miami	Single vehicle
Kentucky	Recreational vehicles
Georgia Tech	Environmental factors
Stanford Research	Intersections
Utah	Post-crash factors
Southwest Research Inst.	Injury causation
New Mexico Oklahoma	Alcohol
California Highway Patrol (1970)	All fatal accidents
HSRI accident data bank	Haphazard sampling
State reporting systems	Limited investigative capability

This point was also addressed in relation to prior multidisciplinary studies in a 1973 SAE paper (Ref. 3) by James O'Day and William L. Carlson of the Highway Safety Research Institute (HSRI) at the University of Michigan. In commenting on the computerized data bank of MDAI (Multi-Disciplinary Accident Investigations) cases at HSRI the authors state:

> "Overall, the MDAI Files are a poor place to look for the frequency of involvement of vehicle defects. The crashes were not selected with the objective of representing any population of crashes."

The authors also discussed results from police-generated accident studies, on the Pennsylvania, Ohio and Indiana Turnpikes. Although the data provide useful insights into the relative importance of various subsystems, they do not provide specific information on such questions as the type of failure in the brake system, or whether a tire defect resulted in tire failure, or simply a skid caused by inadequate tread depth. A broadly-based study to generate estimates of the safety criticality of various vehicle subsystems and components is obviously desirable. Such a study is out-of-scope for the limited objectives of the On-board Sensor Program.

In addition to the special studies described in the O'Day paper, which have been compiled from state police investigations on limited access highways, the individual states are required, as one of the Federal requirements to obtain highway trust fund money, to develop and implement accident data reporting systems within their state. The New Jersey computerized system, which was reviewed in a recent Avco visit is believed to be typical. This system is currently "coming up to speed" in handling police-generated reports for every accident involving property damage exceeding $200. Among the items reported through this system is an assessment by the investigating officer as to whether the accident was caused by vehicle defects. Although the new system does not provide for a subsystem breakdown on defect-caused accidents, the Deputy Director, Mr. Robert McMinn, provided Avco with some earlier data on this breakdown. Although the relative contribution of the various subsystems (brakes, tires, lights, etc.) was in general agreement with the literature, the total for defect caused accidents (about 2.5%) was considerably below* that reported by Indiana and others. Avco's contention, that the explanation for this difference lies in the definition of causes and in the methods of investigation employed by the respective sources, was generally accepted by New Jersey.

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*The 1973 records for New Jersey indicated brakes as an accident cause in 1408 of 179,817 accidents (0.78%). Defects were indicated in 3265 accidents (1.8% of the total). The brake accidents represent 43% of all defect accidents in this data. In 420 in-depth investigations, Indiana found 32 brake defect-related accidents (8% of total) out of 106 vehicle factors/cases (25% of all accidents). The brake defects represented 31% of the total vehicle factors.

It is apparent that other than identifying gross failures, most state accident data systems probably do not define a level of detail sufficient to differentiate between specific components.

2.2.1.2 Accident Case Evaluation

The evaluation of the Indiana study results was performed with the objective of generating quantitative estimates of the number of accidents which might be prevented through sensor application. This evaluation has involved further refinement of the procedures described under criterion 5 of the previous subsection. With this in mind, it is important to review the definitions that have been adopted. Throughout Phases II-V* of the Indiana program, the important factors in each accident have been identified as either casual or severity-increasing, and on the basis of investigator certainty as certain, probable, or possible.

The following discussion is excerpted from the final report for Phase II. (Ref. 4)

> "Causal Factor - A factor which was necessary or sufficient for the accident's occurrence, so that had the factor not been present in the accident sequence, the accident would not have occurred.
>
> Severity-Increasing Factor: A factor which was not necessary or sufficient for the accident's occurrence, so that its removal would not have prevented the accident, but would have reduced severity of the impact which resulted.
>
> The certain-probable-possible judgments are necessarily qualitative, making assigned equivalent probabilities highly arbitrary. However, it is estimated that the certain designation represents about a 95 percent confidence, while probable represents about an 80 percent confidence; no equivalent quantitative representation can be assigned the possible designation. In general, the certain category is not utilized where there is any doubt or difference of opinion whatever. There is, in every case, strong evidence supporting the judgment. The probable category is likewise always supported by good evidence, but either due to the nature of the judgment being made,

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*Phase I used a different set of definitions. Cases from Phase I have not been analyzed for sensor application.

> or due to the necessity of relying on a witness' statement, the credibility of which can only be estimated, or some similar reason, the possibility of error is recognized and expressed by application of the probable rating. The possible category includes all factors the existence and involvement of which are not negated by the evidence, and which logically could have played a role, but for which the role either cannot be determined or is not supported by adequate evidence. The utilization of this category is quite flexible, and judgment is exercised as to whether an entry here is meaningful. If the involvement or existence of a factor is deemed unduly speculative, no entry is made in even the possible category."

In attempting to apply the above "necessarily qualitative" judgment as to whether a defect was involved, Avco has reviewed each of the relevant cases and has used Mr. John Treat* and Mr. Fran Oldham** to provide numerical estimates (for each case), consistent with the qualitative assessment (certain, prob., poss.) made previously***, of the probability that an accident was caused (in the sense defined previously) by the defects in question. This procedure has a precedent in that numerical probabilities were generated by the investigative team as part of the report for Phase V investigations. Where these estimates have been provided by IRPS, they have been used in lieu of estimates by either Avco consultant. In cases where the available information was not adequate to refine the assessment of the original investigators, a figure midway through the probability range has been used.

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*Mr. Treat is currently the director of the Institute for Research in Public Safety at Indiana University, and was a principal investigator throughout the Indiana Tri-Level Investigations.

**Mr. Oldham is an independent consultant. He was the vehicle factors representative during Phase II of the Indiana study, and has also been involved with a number of other accident investigations.

***The probability range associated with the Indiana assessment is as follows:

Assessment	Probability Range
Certain	0.90–1.00
Probable	0.75–0.90
Possible	0.00–0.75 (0.20 was generally used by the Indiana investigators as a lower limit)

In addition to associating numerical probabilities with each case, the following questions have been addressed:

1. Was the driver aware of the defect prior to the accident?
2. Was the defect present at the previous Indiana inspection?
3. Was the defect rejectable under the Indiana inspection code?
4. What sensors (if any) might have detected the condition responsible for the accident?

Based on the answers to these questions, a formal sorting procedure was developed to analyze the cases reviewed. The provisions of this procedure are as follows:

1. Final rankings for sensor applicability are based on a weighted sum of the average of the probabilities estimated by Messrs. Treat and Oldman.
2. Cases involving severity increasing factors are discounted 50 percent.
3. Cases in which the driver was aware of this defect prior to the accident are discounted.

2.2.1.3 Case-By-Case Evaluation

The universe of cases for this study consists of 420 Level C* investigations performed during Phases II-V of the Indiana program. Of this total, 106 were cited by the investigators as involving vehicle factors. Restricting attention to components in the brake, tire, steering, suspension, lighting, and signaling subsystems and elimination of pre-1968 vehicles experiencing total brake failure reduces the number of cases under consideration to 73. Tables 2-3 through 2-8 list the case numbers and Indiana assessments of the cases identified as involving vehicle factors. These tables also identify which cases were excluded from detailed review.

Table 2-9 lists the following results of the individual case reviews:

- two estimates (Treat and Oldham) as to the probability that the accident was caused by the indicated defect,
- the average of these estimates,

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*The Indiana study involved two distinct levels of investigation. The Level C investigations involved post-crash garage inspection of all involved vehicles and detailed driver interviews. The Level B investigations involved principally on-site examination of the vehicles, roadway and driver. Because of the financial constraints of the project there were many more Level B investigations than Level C.

TABLE 2–3. LEVEL C INDIANA CASES INVOLVING BRAKES

On-Site Case No.	In-Depth Case No.	Indiana Assessment		Year	Vehicle Model	Comments
546	082	Probable	S/I	1965	Plymouth Barracuda	Degraded performance
X 555	084	Certain	Causal	1964	Ford F100 Panel Truck	Total failure - master cylinder
X 641	111	Certain	Causal	1949	Chevrolet 3/4-ton	Total failure - wheel cylinder
652	113	Possible	Causal	1967	Oldsmobile Cutlass	Imbalance
710	131	Possible	Causal	1963	Volkswagen	Grabbed/locked, contaminated lining
X 720	133	Probable	Causal	1963	Pontiac	Total failure, front and rear
730	136	Certain	Causal	1955	Chevrolet	Imbalance; contamination; leak
758	144	Certain	Causal	1971	Plymouth Fury II	Imbalance
997	214	Probable	Causal	1968	Pontiac LeMans	Imbalance; wear
1004	210	Probable	Causal	1968	Dodge	Front failure, master cylinder
1018	222	Certain	S/I	1961	Chevrolet	Rear failure, wheel cylinder; frozen*
1027	225	Certain	Causal	1969	Chevrolet Chevelle	Imbalance; proportioning
1030	227	Certain	Causal	1971	Datsun 240Z	Imbalance
2197	045	Probable	Causal	1966	Plymouth	Imbalance; lining wear*
X 2313	068	Certain	Causal	1966	Pontiac	Total failure (hose)
2353	079	Probable	Causal	1964	International Pickup	Brake proportioning (design)
2420	098	Possible	Causal	1960	Ford Falcon	Degraded performance
2447	106	Certain	Causal	1968	Oldsmobile Cutlass	Imbalance
2477	112	Possible	Causal	1965	Ford F100	Degraded performance; clearance
2546	122	Possible	Causal	1960	Chevrolet Pickup	Degraded performance; clearance; contamination*
2567	127	Probable	Causal	1970	Dodge	Pumping required
		Probable	Causal	1970	Dodge	Imbalance
2604	136	Probable	Causal	1969	Chevrolet Camaro	Imbalance
2705	154	Possible	Causal	1968	Dodge Charger	Pumping required; vacuum leak
2941	177	Certain	Causal	1963	Ford Falcon	Total failure - adjuster
3128	197	Possible	Causal	1963	Pontiac Grand Prix	Imbalance
X 3140	199	Certain	Causal	1955	Chevrolet	Hose failure - rubbing
3141	200	Possible	Causal	1966	Chevrolet Corvette	Degraded (other)
X 3432	229	Certain	Causal	1964	Volkswagen	Total failure - wheel cylinder
X 3499	238	Certain	Causal	1965	Ford Mustang	Total failure - hose contacted exhaust
3565	248	Possible	Causal	1973	Mercury	Degraded performance; contamination
3668	263	Possible	Causal	1961	Chevrolet	Imbalance

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* Vehicle cited for defects in other systems.
X Case not reviewed for sensor applicability.

TABLE 2–4. LEVEL C INDIANA CASES INVOLVING TIRES

On-Site Case No.	In-Depth Case No.	Indiana Assessment		Vehicle		Comments
				Year	Model	
643	112	Probable	Causal	1962	Pontiac Tempest	Underinflation
683	120	Probable	Causal	1965	Pontiac Catalina	Underinflation
		Probable	Causal	1965	Pontiac Catalina	Tread depth, right front, right rear
705	129	Probable	Causal	1960	Ford Falcon	Underinflation
710	131	Probable	Causal	1963	Volkswagen	Tread depth*
826	166	Probable	Causal	1964	Ford Galaxie	Underinflation
		Probable	Causal	1964	Ford Galaxie	Tread
842	173	Possible	Causal	1970	Volkswagen Squareback	Overinflation (front)
843	174	Probable	Causal	1971	Pontiac LeMans	Underinflation*
959	201	Probable	Causal	1969	Chevrolet Nova	Underinflation*
1018	222	Certain	S/I	1961	Chevrolet	Tread
2060	001	Possible	Causal	1966	Chevrolet	Underinflation*
2096	011	Possible	Causal	1969	Chevrolet Nova	Tires too large*
X 2105	013	Probable	Causal	1972	Chevrolet Nova	Studded tires, dry pavement
2263	060	Possible	Causal	1973	Fiat	Underinflation
2293	062	Possible	Causal	1966	Pontiac Catalina	Overinflation, left front; underinflation, right front, left rear, right rear
X 2339	073	Possible	Causal	1965	Ford Mustang	Too wide*
2353	079	Probable	Causal	1964	International Pickup	Depth*
2391	091	Probable	Causal	1964	Plymouth	Depth
2515	118	Possible	S/I	1965	Dodge	Depth
2567	127	Possible	Causal	1970	Dodge	Underinflation; wheel bearing play
X 2588	133	Possible	Causal	1970	Ford Maverick	Studded tires, dry pavement
2700	152	Possible	Causal	1973	Buick	Underinflation, rear
2980	185	Possible	Causal	1972	Chevrolet Nova	Underinflation
3169	204	Certain	Causal	1962	Pontiac	Depth
3180	206	Possible	Causal	1964	Plymouth Fury	Underinflation
3210	211	Possible	Causal	1964	Chrysler	Tread
3262	216	Possible	S/I	1969	Karmann-Ghia	Tread
3273	217	Possible	S/I	1969	Ford Fairlane	Overinflation
3310	221	Probable	Causal	1967	American Motors	Tread
3363	223	Probable	Causal	1965	Ford Mustang	Tread
3410	225	Possible	Causal	1970	Chevrolet Malibu	Tread
3460	233	Possible	Causal	1967	Buick	Tread
3701	268	Possible	Causal	1963	Volkswagen	Overinflation*
3712	273	Possible	Causal	1974	Chevrolet Vega	Tread

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* Vehicle cited for defects in other systems.
X Case not reviewed for sensor applicability.

TABLE 2–5. LEVEL C INDIANA CASES INVOLVING LIGHTS/SIGNALS

On-Site Case No.	In-Depth Case No.	Indiana Assessment		Vehicle Year	Model	Comments
604	101	Probable	Causal	1965	Ford	Brake light and directional signals inoperative
752	142	Probable	Causal	1966	Volkswagen Bus	Brake light inoperative
809	161	Possible	Causal	1961	Chevrolet Corvair	Directional signals and brake light
871	171	Possible	Causal	1968	Chevrolet Impala	Dirty rear lights
X 906	187	Possible	Causal	1962	Chevrolet	No side markers
918	189	Probable	Causal	1966	Chevrolet Corvette	Brake light inoperative
2364	083	Possible	Causal	1966	Oldsmobile F-85	Headlight inoperative/misaimed
2377	088	Possible	Causal	1969	Ford Comet Sedan	Directional signals inoperative
2568	128	Possible	Causal	1968	Pontiac Catalina	Back-up light inoperative
2584	132	Possible	Causal	1968	Chevrolet Nomad	Brake light inoperative
2688	150	Possible	Causal	1971	Chevrolet Vega	Brake light inoperative
2953	180	Possible	Causal	1966	Ford Mustang	Back-up light painted
3183	208	Possible	Causal	1967	Oldsmobile	Instrument lights inoperative
3534	241	Possible	Causal	1971	Volkswagen	Horn inoperative

X Case not reviewed for sensor applicability.

TABLE 2–6. LEVEL C INDIANA CASES INVOLVING STEERING

On-Site Case No.	In-Depth Case No.	Indiana Assessment		Year	Vehicle Model	Comments
558	085	Certain	Causal	1965	Volkswagen	Steering free play
798	157	Possible	Causal	1971	Plymouth Fury I	Steering locked
801	158	Possible	Causal	1963	Chevrolet Impala	Steering "other"*
816	163	Probable	Causal	1969	Chevrolet	Play
843	174	Possible	Causal	1971	Pontiac LeMans	Other (power steering feedback) snow
937	193	Possible	Causal	1965	Chevrolet Nova	Play; tie rod ends
2065	003	Possible	Causal	1965	Ford Mustang	Caster wrong due to raised rear end
2096	011	Possible	Causal	1969	Chevrolet Nova	Undersized steering wheel*
2197	045	Probable	Causal	1966	Plymouth	Free play
		Probable	Causal	1966	Plymouth	Power steering inoperative
2353	079	Possible	Causal	1964	International 1200	Play*
2546	122	Possible	Causal	1960	Chevrolet Pick-Up	Play*
2618	138	Possible	Causal	1971	International	Play
3180	206	Possible	Causal	1964	Plymouth Fury	Play
3436	231	Possible	Causal	1955	Buick	Play
3497	237	Possible	Causal	1970	Chevrolet Camaro	Play

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* Vehicle cited for defects in other systems.

TABLE 2–7. LEVEL C INDIANA CASES INVOLVING SUSPENSION

On-Site Case No.	In-Depth Case No.	Indiana Assessment		Vehicle Year	Model	Comments
801	158	Possible	Causal	1963	Chevrolet Impala	Missing/broken shock*
		Possible	Causal	1963	Chevrolet Impala	Ball joints
832	170	Possible	Causal	1970	Ford Mustang	Too stiff suspension
2065	003	Possible	Causal	1965	Ford Mustang	Raised rear; steering*
X 2331	073	Possible	Causal	1965	Ford Mustang	Raised rear
2362	082	Certain	Causal	1967	Chevrolet	Wheel loss
X 3171	205	Possible	Causal	1966	Volkswagen Fastback	Swing axles
X 3701	268	Probable	Causal	1963	Volkswagen Sedan	Swing axles

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* Vehicle cited for defects in other systems.
X Case not reviewed for sensor applicability.

TABLE 2–8. LEVEL C INDIANA CASES INVOLVING OTHER VEHICLE FACTORS

On-Site Case No.	In-Depth Case No.	Indiana Assessment		Vehicle		Comments
				Year	Model	
X 548	083	Possible	Causal	1970	Chevrolet	Power loss
X 561	086	Probable	Causal	1956	Ford F100	Door opened
X 693	124	Possible	Causal	1960	Ford	No mirror
X 886	183	Possible	Causal	1966	Volkswagen	Condensation
X 980	208	Certain	Causal	1963	Volkswagen Bus	Door opened
X 2147	030	Possible	Causal	1972	Dodge Colt	Overload
X 2331	071	Probable	Causal	1971	Chevrolet Chevelle	Window design
X 2373	087	Certain	Causal	1969	Chevrolet Camaro	Power loss
X 2561	125	Possible	Causal	1968	Ford Galaxie	Exhaust leak
X 2562	126	Possible	Causal	1962	Ford Falcon Van	Obstructed vision; no mirror
X 2621	140	Probable	Causal	1973	Ford Pinto	Obstructed vision (fog)
X 2953	180	Probable	Causal	1966	Ford Mustang	Window design
X 3209	210	Probable	Causal	1970	Ford	Accelerator stuck
X 3273	217	Possible	Causal	1966	Ford Mustang	Obstructed vision (fog)*
X 3401	224	Certain	Causal	1972	Pontiac Ventura	Ice on window
X 3554	246	Possible	Causal	1967	Ford LTD	Snow on window
X 3682	266	Possible	Causal		Unknown	Exhaust leak (carbon monoxide)
X 3708	270	Possible	Causal	1966	Ford	Accelerator stuck

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* Vehicle cited for defects in other systems.

X Case not reviewed for sensor applicability.

TABLE 2–9. SUMMARY OF INDIVIDUAL CASE REVIEWS

ON-SITE CASE NO.	IN-DEPTH CASE NO.	PROBABILITY ASSESSMENTS			DRIVER AWARE	SEVERITY INCREASING	RELEVANT SENSORS
		NO. 1	NO. 2	AVG			
546	82	0.80	0.50	0.65		YES	23 28
558	85	0.60	0.90	0.75			3 6 10 11
604	101	0.80	0.80	0.80			37 39
643	112	0.75	0.80	0.77			40
652	113	0.20	0.05	0.12			21 28
683	120	0.75	0.80	0.77			40
683	120	0.75	0.80	0.77	YES		42
705	129	0.75	0.80	0.77			40
710	131	0.75	0.80	0.77			42
710	131	0.40	0.50	0.45			27 28 29
730	136	0.95	0.95	0.95			22 23 28 23A
752	142	0.75	0.75	0.75			30 33 37 39
758	144	0.95	0.95	0.95			
798	157	0.40	0.75	0.57	YES		16A
801	158	0.35	0.50	0.42	YES		10 3
809	161	0.70	0.50	0.60			37 39 30 33
816	163	0.80	0.80	0.80			10 14
826	166	0.75	0.80	0.77			40
826	166	0.80	0.80	0.80	YES		42
832	170	0.05	0.05	0.05	YES		
842	173	0.20	0.10	0.15			40A
843	174	0.20	0.50	0.35	YES		
843	174	0.40	0.80	0.60			40
871	177	0.40	0.20	0.30			37
918	189	0.80	0.75	0.77			37 39
937	193	0.30	0.50	0.40			3 10 11
959	201	0.75	0.90	0.82			40
997	214	0.80	0.80	0.80	YES		21 28 29A
1004	210	0.85	0.85	0.85			28
1018	222	0.95	0.95	0.95		YES	42
1018	222	0.75	0.75	0.75		YES	28 29B
1027	225	0.99	0.95	0.97	YES		21 28
1030	227	0.95	0.95	0.95			21 28
2060	1	0.50	0.50	0.50			40
2065	3	0.20	0.10	0.15	YES		
2096	11	0.50	0.50	0.50			
2197	45	0.40	0.80	0.60			10 16A
2197	45	0.80	0.80	0.80			21 28
2263	60	0.20	0.40	0.30			40
2293	62	0.20	0.05	0.12			40 40A
2293	62	0.10	0.15	0.12			42
2331	73	0.50	0.50	0.50			
2353	79	0.20	0.10	0.15			10 11
2353	79	0.90	0.80	0.85			
2353	79	0.75	0.90	0.82			42
2362	82	0.99	0.99	0.99			
2364	83	0.30	0.10	0.20			17 18
2377	88	0.30	0.10	0.20			30 37
2391	91	0.75	0.15	0.45	YES		42
2420	98	0.20	0.50	0.35			29A 27 23 28
2447	106	0.30	0.05	0.17	YES		21 28 29A
2477	112	0.30	0.05	0.17			23 28 29A 27 21
2515	118	0.20	0.20	0.20	YES	YES	42
2546	122	0.20	0.10	0.15			11
2546	122	0.50	0.60	0.55			27 23 28 23A 29A
2567	127	0.85	0.80	0.82	YES		28 29A 23
2567	127	0.30	0.50	0.40			40
2567	127	0.20	0.05	0.12			1
2568	128	0.20	0.10	0.15			20
2584	132	0.20	0.01	0.10			37 39
2604	136	0.75	0.80	0.77			21 28
2618	138	0.20	0.10	0.15			10 14
2688	150	0.01	0.01	0.01			37 39
2700	152	0.20	0.10	0.15			40
2705	154	0.90	0.90	0.90	YES		22 23 23A 28 29A
2953	180	0.20	0.01	0.10	YES		
2980	185	0.20	0.32	0.26			40
3128	197	0.30	0.20	0.25	YES		21 28
3141	200	0.80	0.80	0.80			
3169	204	0.83	0.83	0.83	YES		42
3180	206	0.20	0.42	0.31	YES		1 10 11
3180	206	0.20	0.01	0.10			40
3183	208	0.10	0.15	0.12	YES		
3210	211	0.20	0.32	0.26	YES		42
3262	216	0.20	0.50	0.35		YES	42
3273	217	0.50	0.60	0.55		YES	40A
3310	221	0.74	0.50	0.62			
3363	223	0.40	0.62	0.51			42
3410	225	0.20	0.24	0.22			42
3436	231	0.20	0.26	0.23			1 10 11
3460	233	0.42	0.42	0.42			42
3497	237	0.38	0.38	0.38			10 11
3534	241	0.20	0.04	0.12	YES		
3565	248	0.24	0.20	0.22			
3668	263	0.33	0.33	0.33		YES	23A 28
3701	268	0.49	0.49	0.49			40A
3712	273	0.20	0.35	0.27	YES		42

- an indication as to whether the driver was aware of the defect prior to the accident*,

- the sensors that might have alerted the driver to the condition implicated in the accident.

Based on the entries in Table 2-9, a sorting exercise has been carried out to collect all cases relevant to each sensor area. The results of this exercise are depicted graphically in Figures 2-2 through 2-5, and numerically in Table 2-10.

The first bar chart on each figure is entitled Number of Cases Cited, and represents the total number of cases in which the prescribed sensor might have detected the cited defect condition. Note that the length of each bar is an integral number of cases.

The second bar chart on each figure is entitled, Number of Unaware Cases. Each column on this chart was prepared by eliminating from consideration those cases in which the vehicle operator was aware of the condition prior to the accident and for which, therefore, the application of a sensor to detect the condition would be redundant. Again, the number of cases on this chart is an integer for each bar.

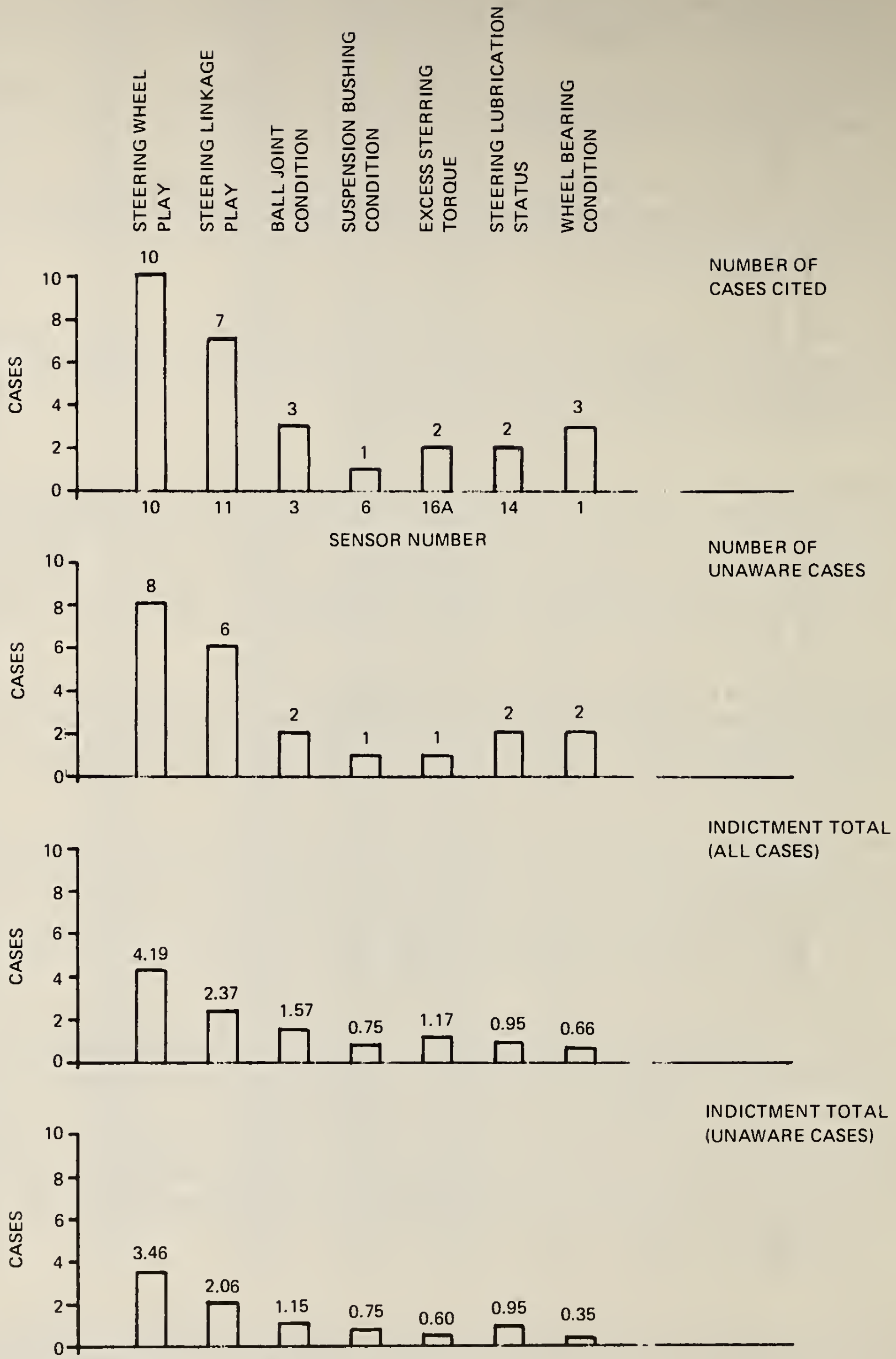
The third bar chart on each figure is entitled, "Indictment Total". Here, each case cited was weighted by the strength of indictment expressed on a probability, (i.e., the investigators certainty that the accident could have been eliminated by eliminating the defect).

The final bar chart on each of the four figures is a combination of awareness and indictment weighing; and is labeled "Unaware Indictment Total". Here the indictment was used as a weighing factor only on those cases in which the driver was unaware of the defect prior to the accident. Cases in which the driver was aware have been eliminated.

These figures illustrate how the relative ranking of sensor concepts changes with the method of evaluation. For highly visible defects, the case total shrinks when aware cases are excluded. Other defects tend to be indicated more strongly than their counterparts. The final evaluation (for Task 2 purposes) has been based on the unaware indictment total for each potential sensor area, i.e., the bottom row of graphs on each figure. This appears to be the most generally useful measure of the sensor's potential impact.

---

*This determination was based on the driver interview, which explicitly asked whether any defects were present prior to the accident. Although some drivers were unreliable or unresponsive, the interviewers were generally able to identify inaccurate responses to questions.



86-2623

Figure 2–2 STEERING AND SUSPENSION SENSORS

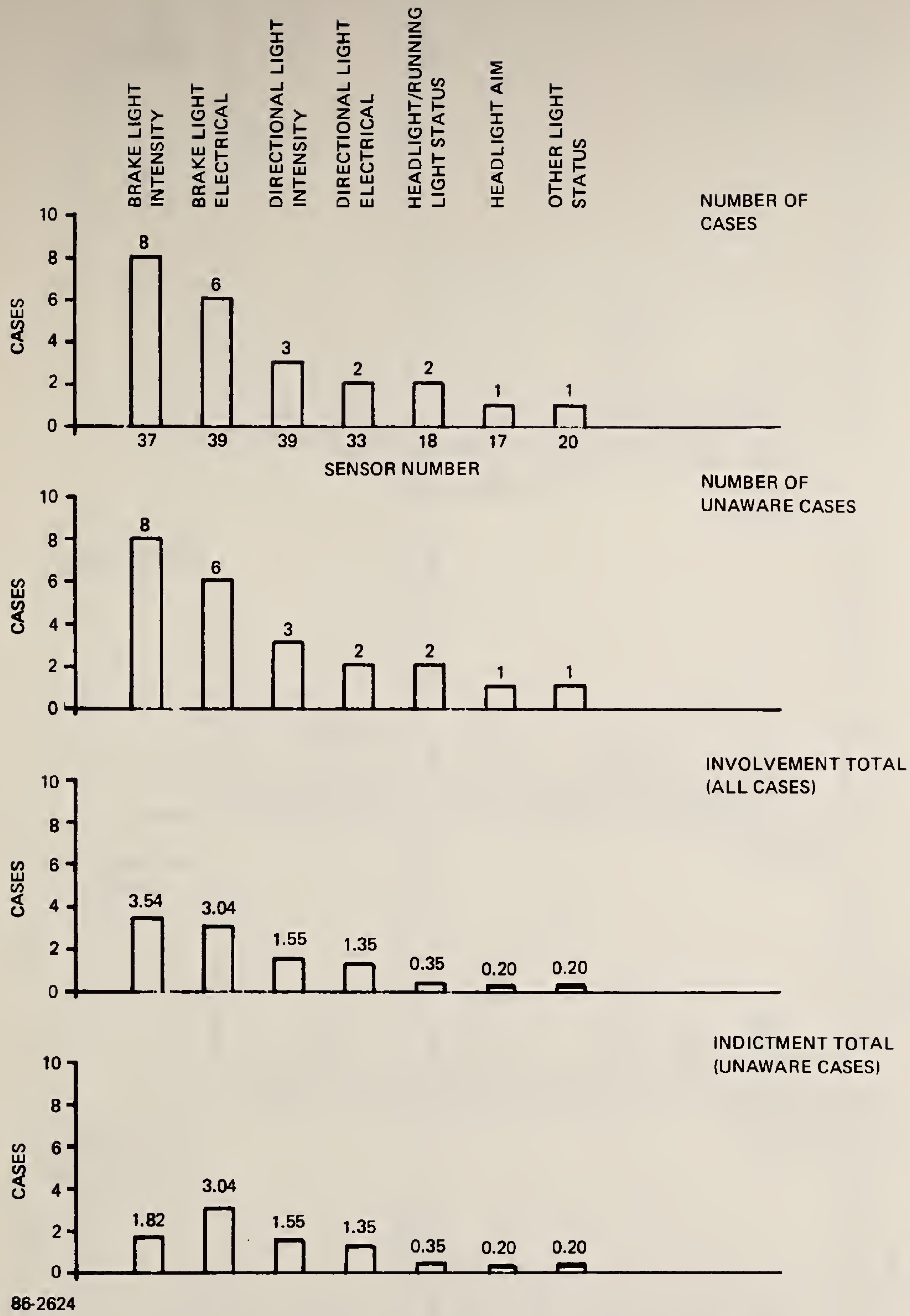
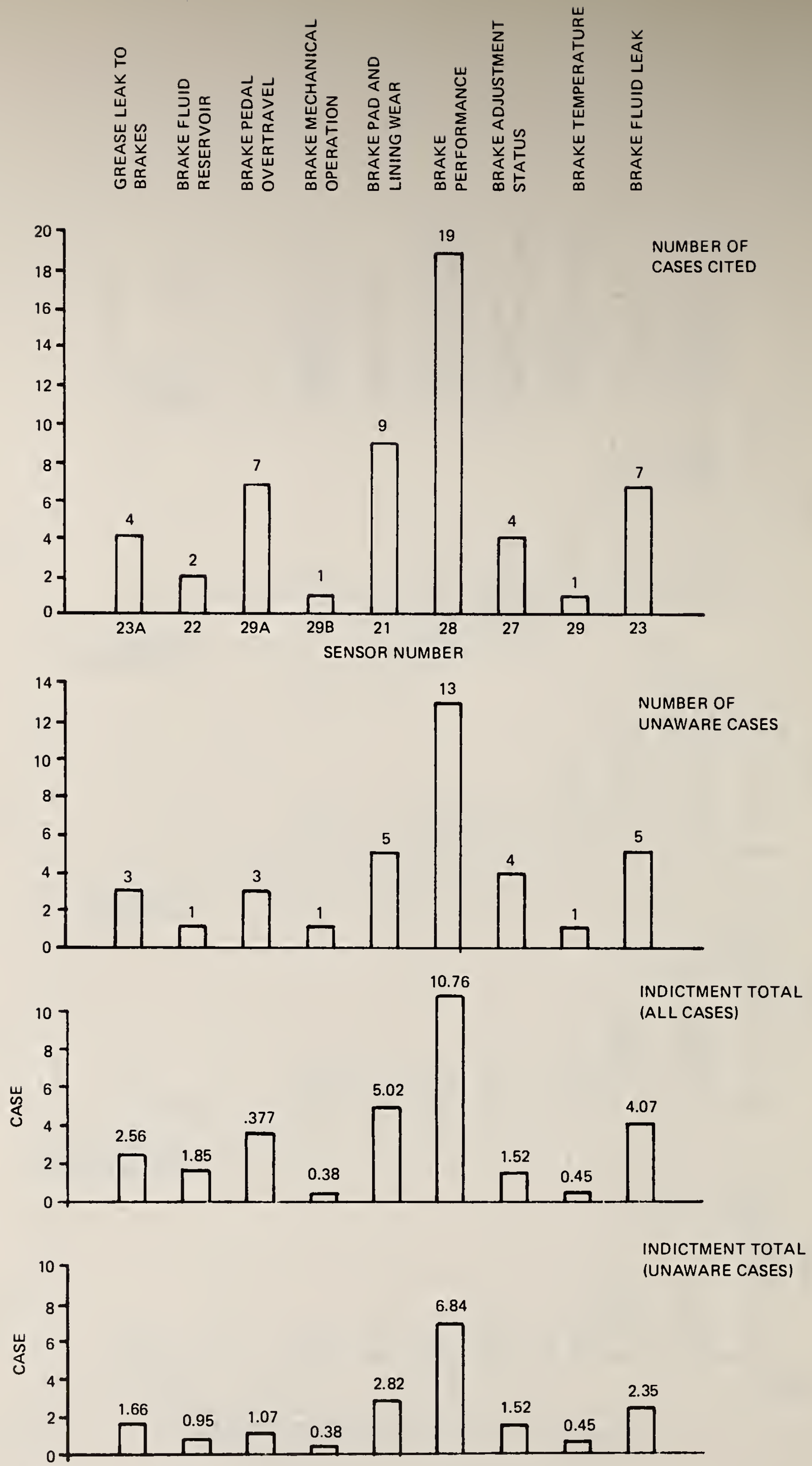
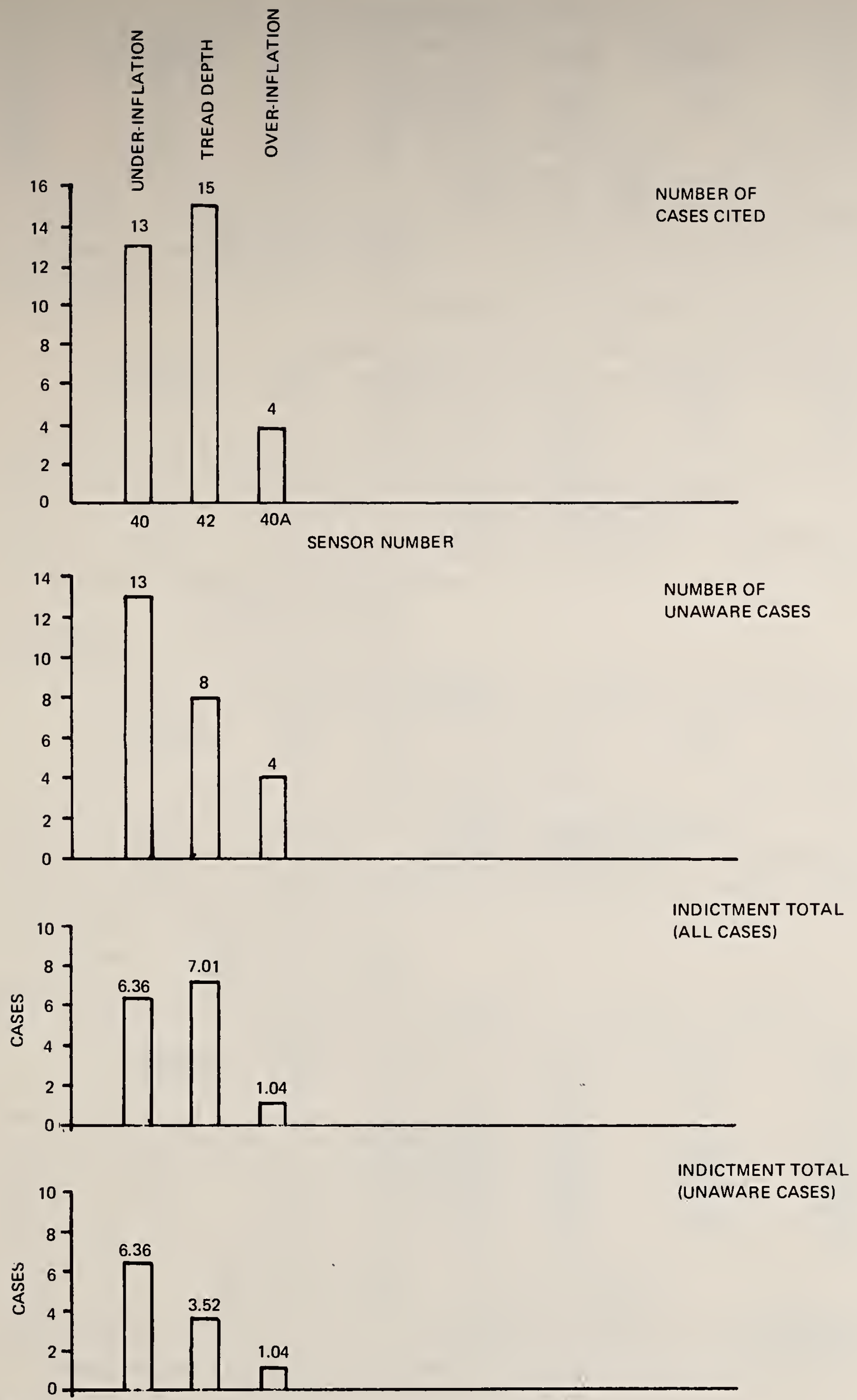


Figure 2–3 LIGHTING AND SIGNALING SENSORS



86-2625

Figure 2–4 BRAKE SENSORS



86-2626

Figure 2–5 TIRE SENSORS

TABLE 2–10. SENSOR EVALUATION BASED ON INDIANA ACCIDENT ANALYSIS

```
CASES  RELEVANT  TO  SENSOR   1  -- WHEEL BEARING CONDITION

ON-SITE      IN-DEPTH    PROBABILITY ASSESSMENTS   DRIVER     SEVERITY
CASE NO.     CASE NO.      NO. 1   NO. 2    AVG    AWARE     INCREASING

 2567          127          0.20    0.05   0.12
 3180          206          0.20    0.42   0.31     YES
 3436          231          0.20    0.26   0.23

CASES  CITED=    3 CASES UNAWARE=    2

                         PROBABILITY TOTALS
                         NO. 1   NO. 2   AVG
ALL CASES                0.60    0.73    0.66
UNAWARE CASES            0.40    0.31    0.35

TOTAL  VARIANCE=   0.07 VARIANCE OF DISAGREEMENT=   0.01 STD DEV OF COUNT=   1.04
```

```
CASES  RELEVANT  TO  SENSOR   3 -- BALL JOINT CONDITION

ON-SITE      IN-DEPTH    PROBABILITY ASSESSMENTS   DRIVER     SEVERITY
CASE NO.     CASE NO.      NO. 1   NO. 2    AVG    AWARE     INCREASING

  558           85          0.60    0.90   0.75
  801          158          0.35    0.50   0.42     YES
  937          193          0.30    0.50   0.40

CASES  CITED=    3 CASES UNAWARE=    2

                         PROBABILITY TOTALS
                         NO. 1   NO. 2   AVG
ALL CASES                1.25    1.90    1.57
UNAWARE CASES            0.90    1.40    1.15

TOTAL  VARIANCE=   0.75 VARIANCE OF DISAGREEMENT=   0.03 STD DEV OF COUNT=   1.32
```

```
CASES  RELEVANT  TO  SENSOR   6  --  SUSPENSION BUSHING CONDITION

ON-SITE      IN-DEPTH    PROBABILITY ASSESSMENTS   DRIVER     SEVERITY
CASE NO.     CASE NO.      NO. 1   NO. 2    AVG    AWARE     INCREASING

  558           85          0.60    0.90   0.75

CASES  CITED=    1 CASES UNAWARE=    1

                         PROBABILITY TOTALS
                         NO. 1   NO. 2   AVG
ALL CASES                0.60    0.90    0.75
UNAWARE CASES            0.60    0.90    0.75

TOTAL  VARIANCE=   0.58 VARIANCE OF DISAGREEMENT=   0.02 STD DEV OF COUNT=   1.26
```

```
CASES  RELEVANT  TO  SENSOR  10 -- DIRECTIONAL LIGHT INTENSITY

ON-SITE      IN-DEPTH    PROBABILITY ASSESSMENTS   DRIVER     SEVERITY
CASE NO.     CASE NO.      NO. 1   NO. 2    AVG    AWARE     INCREASING

  558           85          0.60    0.90   0.75
  801          158          0.35    0.50   0.42     YES
  816          163          0.80    0.80   0.80
  937          193          0.30    0.50   0.40
 2197           45          0.40    0.80   0.60
 2353           79          0.20    0.10   0.15
 2618          138          0.20    0.10   0.15
 3180          206          0.20    0.42   0.31     YES
 3436          231          0.20    0.26   0.23
 3497          237          0.38    0.38   0.38

CASES  CITED=  10 CASES UNAWARE=    8

                         PROBABILITY TOTALS
                         NO. 1   NO. 2   AVG
ALL CASES                3.63    4.76    4.19
UNAWARE CASES            3.08    3.84    3.46

TOTAL  VARIANCE=   2.02 VARIANCE OF DISAGREEMENT=   0.08 STD DEV OF COUNT=   1.74
```

TABLE 2–10. (Cont'd)

```
CASES RELEVANT TO SENSOR 11 -- STEERING LINKAGE CONDITION

ON-SITE     IN-DEPTH     PROBABILITY ASSESSMENTS    DRIVER     SEVERITY
CASE NO.    CASE NO.      NO. 1   NO. 2     AVG     AWARE      INCREASING

  558          85          0.60    0.90    0.75
  937         193          0.30    0.50    0.40
 2353          79          0.20    0.10    0.15
 2546         122          0.20    0.10    0.15
 3180         206          0.20    0.42    0.31     YES
 3436         231          0.20    0.26    0.23
 3497         237          0.38    0.38    0.38

CASES CITED=    7 CASES UNAWARE=    6

                         PROBABILITY TOTALS
                         NO. 1   NO. 2   AVG
ALL CASES                2.08    2.66    2.37
UNAWARE CASES            1.88    2.24    2.06

TOTAL VARIANCE=   0.99 VARIANCE OF DISAGREEMENT=   0.04 STD DEV OF COUNT=   1.41
```

```
CASES RELEVANT TO SENSOR 14 -- STEERING LUBRICATION STATUS

ON-SITE     IN-DEPTH     PROBABILITY ASSESSMENTS    DRIVER     SEVERITY
CASE NO.    CASE NO.      NO. 1   NO. 2     AVG     AWARE      INCREASING

  816         163          0.80    0.80    0.80
 2618         138          0.20    0.10    0.15

CASES CITED=    2 CASES UNAWARE=    2

                         PROBABILITY TOTALS
                         NO. 1   NO. 2   AVG
ALL CASES                1.00    0.90    0.95
UNAWARE CASES            1.00    0.90    0.95

TOTAL VARIANCE=   0.66 VARIANCE OF DISAGREEMENT=   0.00 STD DEV OF COUNT=   1.29
```

```
CASES RELEVANT TO SENSOR 16A -- EXCESS STEERING TORQUE

ON-SITE     IN-DEPTH     PROBABILITY ASSESSMENTS    DRIVER     SEVERITY
CASE NO.    CASE NO.      NO. 1   NO. 2     AVG     AWARE      INCREASING

  798         157          0.40    0.75    0.57     YES
 2197          45          0.40    0.80    0.60

CASES CITED=    2 CASES UNAWARE=    1

                         PROBABILITY TOTALS
                         NO. 1   NO. 2   AVG
ALL CASES                0.80    1.55    1.17
UNAWARE CASES            0.40    0.80    0.60

TOTAL VARIANCE=   0.40 VARIANCE OF DISAGREEMENT=   0.04 STD DEV OF COUNT=   1.18
```

```
CASES RELEVANT TO SENSOR 17 -- HEADLIGHT AIM

ON-SITE     IN-DEPTH     PROBABILITY ASSESSMENTS    DRIVER     SEVERITY
CASE NO.    CASE NO.      NO. 1   NO. 2     AVG     AWARE      INCREASING

 2364          83          0.30    0.10    0.20

CASES CITED=    1 CASES UNAWARE=    1

                         PROBABILITY TOTALS
                         NO. 1   NO. 2   AVG
ALL CASES                0.30    0.10    0.20
UNAWARE CASES            0.30    0.10    0.20

TOTAL VARIANCE=   0.05 VARIANCE OF DISAGREEMENT=   0.01 STD DEV OF COUNT=   1.02
```

TABLE 2–10. (Cont'd)

```
CASES RELEVANT TO SENSOR 18 -- HEADLIGHT/RUNNING LIGHT STATUS

ON-SITE      IN-DEPTH     PROBABILITY ASSESSMENTS     DRIVER      SEVERITY
CASE NO.     CASE NO.       NO. 1    NO. 2     AVG     AWARE      INCREASING

 2364           83          0.30     0.10     0.20

CASES CITED=    1 CASES UNAWARE=    1

                           PROBABILITY TOTALS
                           NO. 1   NO. 2   AVG
ALL CASES                  0.30    0.10    0.20
UNAWARE CASES              0.30    0.10    0.20

TOTAL VARIANCE=   0.05 VARIANCE OF DISAGREEMENT=   0.01 STD DEV OF COUNT=   1.02



CASES RELEVANT TO SENSOR 20 -- OTHER LIGHT STATUS

ON-SITE      IN-DEPTH     PROBABILITY ASSESSMENTS     DRIVER      SEVERITY
CASE NO.     CASE NO.       NO. 1    NO. 2     AVG     AWARE      INCREASING

 2568          128          0.20     0.10     0.15

CASES CITED=    1 CASES UNAWARE=    1

                           PROBABILITY TOTALS
                           NO. 1   NO. 2   AVG
ALL CASES                  0.20    0.10    0.15
UNAWARE CASES              0.20    0.10    0.15

TOTAL VARIANCE=   0.02 VARIANCE OF DISAGREEMENT=   0.00 STD DEV OF COUNT=   1.01



CASES RELEVANT TO SENSOR 21 -- BRAKE PAD AND LINING WEAR

ON-SITE      IN-DEPTH     PROBABILITY ASSESSMENTS     DRIVER      SEVERITY
CASE NO.     CASE NO.       NO. 1    NO. 2     AVG     AWARE      INCREASING

  652          113          0.20     0.05     0.12
  997          214          0.80     0.80     0.80     YES
 1027          225          0.99     0.95     0.97     YES
 1030          227          0.95     0.95     0.95
 2197           45          0.80     0.80     0.80
 2447          106          0.30     0.05     0.17     YES
 2477          112          0.30     0.05     0.17
 2604          136          0.75     0.80     0.77
 3128          197          0.30     0.20     0.25     YES

CASES CITED=    9 CASES UNAWARE=    5

                           PROBABILITY TOTALS
                           NO. 1   NO. 2   AVG
ALL CASES                  5.39    4.65    5.02
UNAWARE CASES              3.00    2.65    2.82

TOTAL VARIANCE=   2.19 VARIANCE OF DISAGREEMENT=   0.02 STD DEV OF COUNT=   1.79



CASES RELEVANT TO SENSOR 22 -- BRAKE FLUID RESERVOIR

ON-SITE      IN-DEPTH     PROBABILITY ASSESSMENTS     DRIVER      SEVERITY
CASE NO.     CASE NO.       NO. 1    NO. 2     AVG     AWARE      INCREASING

  730          136          0.95     0.95     0.95
 2705          154          0.90     0.90     0.90     YES

CASES CITED=    2 CASES UNAWARE=    1

                           PROBABILITY TOTALS
                           NO. 1   NO. 2   AVG
ALL CASES                  1.85    1.85    1.85
UNAWARE CASES              0.95    0.95    0.95

TOTAL VARIANCE=   0.90 VARIANCE OF DISAGREEMENT=   0.0  STD DEV OF COUNT=   1.38
```

TABLE 2–10. (Cont'd)

```
CASES RELEVANT TO SENSOR 23 -- BRAKE FLUID LEAK

ON-SITE     IN-DEPTH     PROBABILITY ASSESSMENTS    DRIVER     SEVERITY
CASE NO.    CASE NO.      NO. 1    NO. 2    AVG     AWARE      INCREASING

  546          82         0.80     0.50    0.65                YES
  730         136         0.95     0.95    0.95
 2420          98         0.20     0.50    0.35
 2477         112         0.30     0.05    0.17
 2546         122         0.50     0.60    0.55
 2567         127         0.85     0.80    0.82     YES
 2705         154         0.90     0.90    0.90     YES

CASES CITED=   7 CASES UNAWARE=   5

                      PROBABILITY TOTALS
                      NO. 1   NO. 2   AVG
ALL CASES             4.50    4.30    4.07
UNAWARE CASES         2.75    2.60    2.35

TOTAL VARIANCE=  1.50 VARIANCE OF DISAGREEMENT=  0.05 STD DEV OF COUNT=  1.58
```

```
CASES RELEVANT TO SENSOR 23A -- GREASE LEAK TO BRAKES

ON-SITE     IN-DEPTH     PROBABILITY ASSESSMENTS    DRIVER     SEVERITY
CASE NO.    CASE NO.      NO. 1    NO. 2    AVG     AWARE      INCREASING

  730         136         0.95     0.95    0.95
 2546         122         0.50     0.60    0.55
 2705         154         0.90     0.90    0.90     YES
 3668         263         0.33     0.33    0.33                YES

CASES CITED=   4 CASES UNAWARE=   3

                      PROBABILITY TOTALS
                      NO. 1   NO. 2   AVG
ALL CASES             2.68    2.78    2.56
UNAWARE CASES         1.78    1.88    1.66

TOTAL VARIANCE=  1.23 VARIANCE OF DISAGREEMENT=  0.00 STD DEV OF COUNT=  1.49
```

```
CASES RELEVANT TO SENSOR 27 -- BRAKE ADJUSTMENT STATUS

ON-SITE     IN-DEPTH     PROBABILITY ASSESSMENTS    DRIVER     SEVERITY
CASE NO.    CASE NO.      NO. 1    NO. 2    AVG     AWARE      INCREASING

  710         131         0.40     0.50    0.45
 2420          98         0.20     0.50    0.35
 2477         112         0.30     0.05    0.17
 2546         122         0.50     0.60    0.55

CASES CITED=   4 CASES UNAWARE=   4

                      PROBABILITY TOTALS
                      NO. 1   NO. 2   AVG
ALL CASES             1.40    1.65    1.52
UNAWARE CASES         1.40    1.65    1.52

TOTAL VARIANCE=  0.70 VARIANCE OF DISAGREEMENT=  0.04 STD DEV OF COUNT=  1.30
```

```
CASES RELEVANT TO SENSOR 28 -- BRAKE PERFORMANCE

ON-SITE     IN-DEPTH     PROBABILITY ASSESSMENTS    DRIVER     SEVERITY
CASE NO.    CASE NO.      NO. 1    NO. 2    AVG     AWARE      INCREASING
  546          82         0.80     0.50    0.65                YES
  652         113         0.20     0.05    0.12
  710         131         0.40     0.50    0.45
  730         136         0.95     0.95    0.95
  997         214         0.80     0.80    0.80     YES
 1004         210         0.85     0.85    0.85
 1018         222         0.75     0.75    0.75                YES
 1027         225         0.99     0.95    0.97     YES
 1030         227         0.95     0.95    0.95
 2197          45         0.80     0.80    0.80
 2420          98         0.20     0.50    0.35
 2447         106         0.30     0.05    0.17     YES
 2477         112         0.30     0.05    0.17
 2546         122         0.50     0.60    0.55
 2567         127         0.85     0.80    0.82     YES
 2604         136         0.75     0.80    0.77
 2705         154         0.90     0.90    0.90     YES
 3128         197         0.30     0.20    0.25     YES
 3668         263         0.33     0.33    0.33                YES
CASES CITED=  19 CASES UNAWARE=  13

                      PROBABILITY TOTALS
                      NO. 1   NO. 2   AVG
ALL CASES            11.92   11.33   10.76
UNAWARE CASES         7.78    7.63    6.84

TOTAL VARIANCE=  4.67 VARIANCE OF DISAGREEMENT=  0.05 STD DEV OF COUNT=  2.38
```

TABLE 2–10. (Cont'd)

```
CASES RELEVANT TO SENSOR 29 -- BRAKE TEMPERATURE

ON-SITE     IN-DEPTH    PROBABILITY ASSESSMENTS   DRIVER     SEVERITY
CASE NO.    CASE NO.     NO. 1   NO. 2     AVG    AWARE     INCREASING

  710          131        0.40    0.50    0.45

CASES CITED=    1 CASES UNAWARE=    1

                        PROBABILITY TOTALS
                        NO. 1   NO. 2   AVG
ALL CASES               0.40    0.50    0.45
UNAWARE CASES           0.40    0.50    0.45

TOTAL VARIANCE=  0.20 VARIANCE OF DISAGREEMENT=  0.00 STD DEV OF COUNT=  1.10
```

```
CASES RELEVANT TO SENSOR 29A -- BRAKE PEDAL OVERTRAVEL

ON-SITE     IN-DEPTH    PROBABILITY ASSESSMENTS   DRIVER     SEVERITY
CASE NO.    CASE NO.     NO. 1   NO. 2     AVG    AWARE     INCREASING

  997          214        0.80    0.80    0.80    YES
 2420           98        0.20    0.50    0.35
 2447          106        0.30    0.05    0.17    YES
 2477          112        0.30    0.05    0.17
 2546          122        0.50    0.60    0.55
 2567          127        0.85    0.80    0.82    YES
 2705          154        0.90    0.90    0.90    YES

CASES CITED=    7 CASES UNAWARE=    3

                        PROBABILITY TOTALS
                        NO. 1   NO. 2   AVG
ALL CASES               3.85    3.70    3.77
UNAWARE CASES           1.00    1.15    1.07

TOTAL VARIANCE=  0.49 VARIANCE OF DISAGREEMENT=  0.04 STD DEV OF COUNT=  1.22
```

```
CASES RELEVANT TO SENSOR 29B -- BRAKE MECHANICAL OPERATION

ON-SITE     IN-DEPTH    PROBABILITY ASSESSMENTS   DRIVER     SEVERITY
CASE NO.    CASE NO.     NO. 1   NO. 2     AVG    AWARE     INCREASING

 1018          222        0.75    0.75    0.75              YES

CASES CITED=    1 CASES UNAWARE=    1

                        PROBABILITY TOTALS
                        NO. 1   NO. 2   AVG
ALL CASES               0.75    0.75    0.38
UNAWARE CASES           0.75    0.75    0.38

TOTAL VARIANCE=  0.14 VARIANCE OF DISAGREEMENT=  0.0   STD DEV OF COUNT=  1.07
```

```
CASES RELEVANT TO SENSOR 30 -- DIRECTIONAL LIGHT INTENSITY

ON-SITE     IN-DEPTH    PROBABILITY ASSESSMENTS   DRIVER     SEVERITY
CASE NO.    CASE NO.     NO. 1   NO. 2     AVG    AWARE     INCREASING

  752          142        0.75    0.75    0.75
  809          161        0.70    0.50    0.60
 2377           88        0.30    0.10    0.20

CASES CITED=    3 CASES UNAWARE=    3

                        PROBABILITY TOTALS
                        NO. 1   NO. 2   AVG
ALL CASES               1.75    1.35    1.55
UNAWARE CASES           1.75    1.35    1.55

TOTAL VARIANCE=  0.98 VARIANCE OF DISAGREEMENT=  0.02 STD DEV OF COUNT=  1.41
```

TABLE 2–10. (Cont'd)

```
CASES  RELEVANT  TO  SENSOR  33  -- DIRECTIONAL LIGHT ELECTRICAL

ON-SITE       IN-DEPTH     PROBABILITY ASSESSMENTS   DRIVER      SEVERITY
CASE NO.      CASE NO.       NO. 1   NO. 2     AVG    AWARE      INCREASING

  752            142          0.75    0.75    0.75
  809            161          0.70    0.50    0.60

CASES  CITED=    2 CASES UNAWARE=    2

                          PROBABILITY TOTALS
                          NO. 1   NO. 2   AVG
ALL CASES                 1.45    1.25    1.35
UNAWARE CASES             1.45    1.25    1.35

TOTAL  VARIANCE=   0.93 VARIANCE OF DISAGREEMENT=   0.01 STD DEV OF COUNT=   1.39
```

```
CASES  RELEVANT  TO  SENSOR  37  -- BRAKE LIGHT INTENSITY

ON-SITE       IN-DEPTH     PROBABILITY ASSESSMENTS   DRIVER      SEVERITY
CASE NO.      CASE NO.       NO. 1   NO. 2     AVG    AWARE      INCREASING

  604            101          0.80    0.80    0.80
  752            142          0.75    0.75    0.75
  809            161          0.70    0.50    0.60
  871            177          0.40    0.20    0.30
  918            189          0.80    0.75    0.77
 2377             88          0.30    0.10    0.20
 2584            132          0.20    0.01    0.10
 2688            150          0.01    0.01    0.01

CASES  CITED=    8 CASES UNAWARE=    8

                          PROBABILITY TOTALS
                          NO. 1   NO. 2   AVG
ALL CASES                 3.96    3.12    3.54
UNAWARE CASES             3.96    3.12    3.54

TOTAL  VARIANCE=   2.32 VARIANCE OF DISAGREEMENT=   0.04 STD DEV OF COUNT=   1.82
```

```
CASES  RELEVANT  TO  SENSOR  39  -- BRAKE LIGHT ELECTRICAL

ON-SITE       IN-DEPTH     PROBABILITY ASSESSMENTS   DRIVER      SEVERITY
CASE NO.      CASE NO.       NO. 1   NO. 2     AVG    AWARE      INCREASING

  604            101          0.80    0.80    0.80
  752            142          0.75    0.75    0.75
  809            161          0.70    0.50    0.60
  918            189          0.80    0.75    0.77
 2584            132          0.20    0.01    0.10
 2688            150          0.01    0.01    0.01

CASES  CITED=    6 CASES UNAWARE=    6

                          PROBABILITY TOTALS
                          NO. 1   NO. 2   AVG
ALL CASES                 3.26    2.82    3.04
UNAWARE CASES             3.26    2.82    3.04

TOTAL  VARIANCE=   2.17 VARIANCE OF DISAGREEMENT=   0.02 STD DEV OF COUNT=   1.78
```

```
CASES  RELEVANT  TO  SENSOR  40  -- TIRE PRESSURE

ON-SITE       IN-DEPTH     PROBABILITY ASSESSMENTS   DRIVER      SEVERITY
CASE NO.      CASE NO.       NO. 1   NO. 2     AVG    AWARE      INCREASING

  643            112          0.75    0.80    0.77
  683            120          0.75    0.80    0.77
  705            129          0.75    0.80    0.77
  826            166          0.75    0.80    0.77
  843            174          0.40    0.80    0.60
  959            201          0.75    0.90    0.82
 2060              1          0.50    0.50    0.50
 2263             60          0.20    0.40    0.30
 2293             62          0.20    0.05    0.12
 2567            127          0.30    0.50    0.40
 2700            152          0.20    0.10    0.15
 2980            185          0.20    0.32    0.26
 3180            206          0.20    0.01    0.10

CASES  CITED=   13 CASES UNAWARE=   13

                          PROBABILITY TOTALS
                          NO. 1   NO. 2   AVG
ALL CASES                 5.95    6.78    6.36
UNAWARE CASES             5.95    6.78    6.36

TOTAL  VARIANCE=   4.06 VARIANCE OF DISAGREEMENT=   0.09 STD DEV OF COUNT=   2.25
```

TABLE 2–10. (Concl'd)

```
CASES  RELEVANT  TO  SENSOR  40A  -- TIRE OVERPRESSURE

ON-SITE      IN-DEPTH    PROBABILITY ASSESSMENTS   DRIVER     SEVERITY
CASE NO.     CASE NO.     NO. 1    NO. 2     AVG   AWARE     INCREASING

  842          173         0.20     0.10     0.15
 2293           62         0.20     0.05     0.12
 3273          217         0.50     0.60     0.55                YES
 3701          268         0.49     0.49     0.49

CASES  CITED=    4 CASES  UNAWARE=    4

                         PROBABILITY  TOTALS
                         NO. 1   NO. 2   AVG
ALL  CASES               1.39    1.24    1.04
UNAWARE  CASES           1.39    1.24    1.04

TOTAL  VARIANCE=   0.36  VARIANCE  OF  DISAGREEMENT=   0.01  STD  DEV  OF  COUNT=   1.17


CASES  RELEVANT  TO  SENSOR  42  -- TIRE TREAD DEPTH

ON-SITE      IN-DEPTH    PROBABILITY ASSESSMENTS   DRIVER     SEVERITY
CASE NO.     CASE NO.     NO. 1    NO. 2     AVG   AWARE     INCREASING

  683          120         0.75     0.80     0.77   YES
  710          131         0.75     0.80     0.77
  826          166         0.80     0.80     0.80   YES
 1018          222         0.95     0.95     0.95              YES
 2293           62         0.10     0.15     0.12
 2353           79         0.75     0.90     0.82
 2391           91         0.75     0.15     0.45   YES
 2515          118         0.20     0.20     0.20   YES        YES
 3169          204         0.83     0.83     0.83   YES
 3210          211         0.20     0.32     0.26   YES
 3262          216         0.20     0.50     0.35              YES
 3363          223         0.40     0.62     0.51
 3410          225         0.20     0.24     0.22
 3460          233         0.42     0.42     0.42
 3712          273         0.20     0.35     0.27   YES

CASES  CITED=   15 CASES  UNAWARE=    8

                         PROBABILITY  TOTALS
                         NO. I   NO. 2   AVG
ALL  CASES               7.50    8.03    7.01
UNAWARE  CASES           3.77    4.58    3.52

TOTAL  VARIANCE=   2.04  VARIANCE  OF  DISAGREEMENT=   0.02  STD  DEV  OF  COUNT=   1.74
```

The results of rank ordering the entire sensor list according to the unaware indictment total are shown in Table 2-11 and Figure 2-6. In addition, Table 2-11 tabulates the information plotted previously: (Number of cases cited, Number of Unaware Cases, and Indictment Total). Moreover, Table 2-11 contains two additional pieces of information transcribed from Table 2-10. The columns labeled σ and σ_D represent one-sigma uncertainties in the unaware indictment total. The former (σ) corresponds to the uncertainty arising from three sources: Finite sample, certainty of indictment, and disagreement between the two analysts. The latter (σ_D) corresponds to the disagreement term only. It is evident that disagreement is not a significant contributor to the total variance. The brackets in Figure 2-6 correspond to plus and minus one-sigma (σ) uncertainties in the unaware indictment totals, and may be used as visual indicators of the statistical certainty of the results.

The entries in Table 2-11 refer to the weighed number of cases identified from the Level C population of 420 cases. Each 2.1 cases, therefore, represents one-half percent of the sample. Of the initial list of 44 potential sensor areas, 25 have appeared in one or more cases. Based on the unaware indictment totals, the top 8 of these exceed one-half percent (2.1 cases) and are considered to have qualified for further investigation.

2.2.1.4 Discussion of Results

Having concluded that the Indiana data are the best available, and subsequently examining a portion of it in detail, it should follow that results derived from it are the best available. But are they adequate? Critics of the Indiana program have made comments like: "No national estimates based on Indiana data can have any validity", basing their objection on deficiencies in sampling methodology and differences between the test region (Monroe County, Ind.) and national average statistics. On the other hand, it is one thing to identify a methodological deficiency and something else again to demonstrate that it makes a difference in the results. Until the deficiencies identified are shown to bias the results, we believe that the data should be accepted, albeit with an understanding of its limitations.

Actually, the rigor/representativeness of the Indiana accident sample represents only one of the limitations of this data. A more complete list of its limitations would include the following factors:

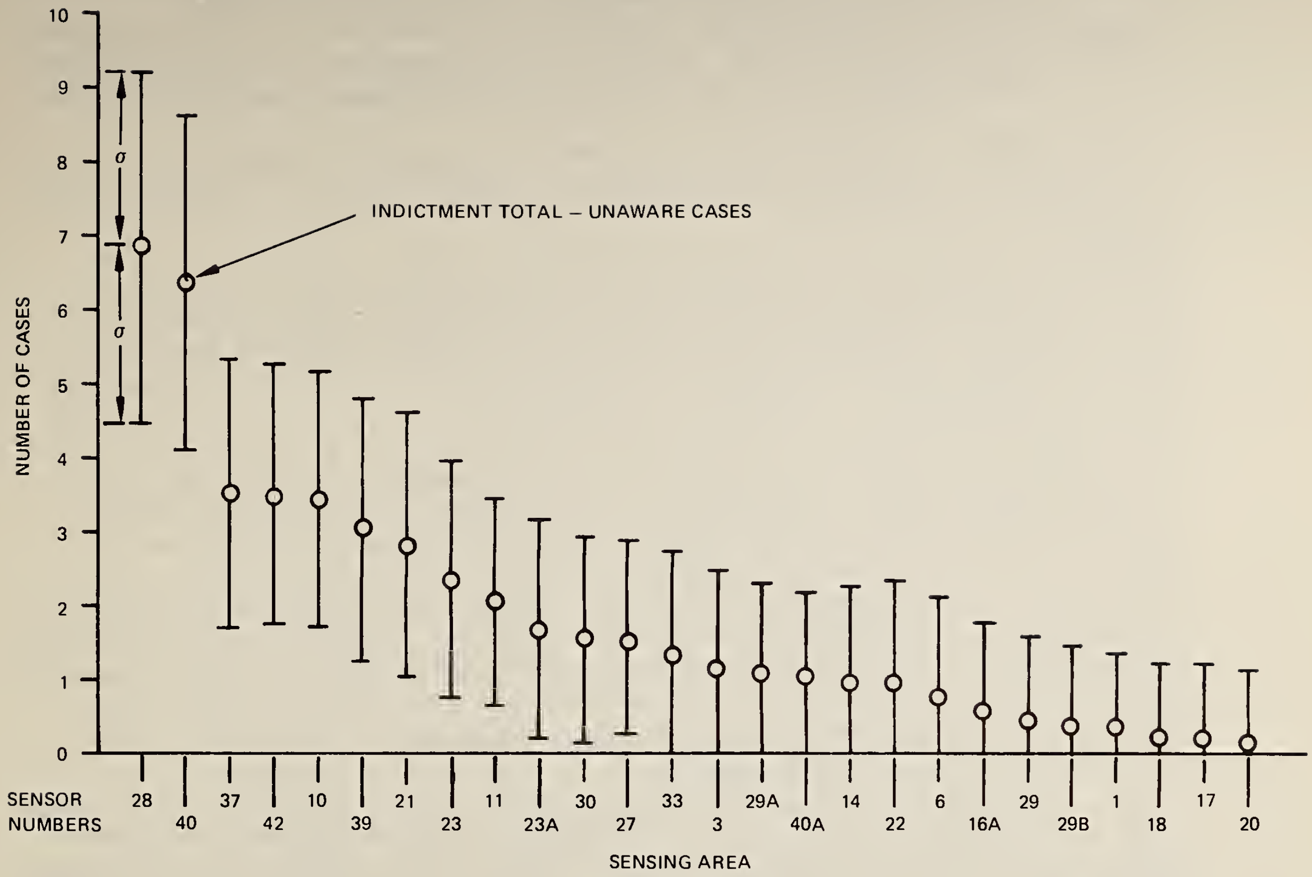
1. Quantity (number of cases in sample).

2. Currency (i.e., applicability to present and future automobiles).

3. Generality (representation of this data as a description of national conditions).

TABLE 2–11. RESULTS OF ACCIDENT CASE ANALYSIS

Rank	Sensor Number	Description	Indictment Total		Cases	Unaware	σ	σ_D
			Unaware Cases	All Cases				
1	28	Brake Performance	6.84	10.76	19	13	2.38	0.22
2	40	Tire Pressure (Underinflated)	6.36	6.36	13	13	2.25	0.30
3	37	Brake Light Intensity	3.54	3.54	8	8	1.82	0.20
4	42	Tire Tread Depth	3.52	7.01	15	8	1.74	0.14
5	10	Steering Wheel Play	3.46	4.19	10	8	1.74	0.28
6	39	Brake Light Electrical	3.04	3.04	6	6	1.78	0.14
7	21	Brake Pad and Lining Wear	2.82	5.02	9	5	1.79	0.14
8	23	Brake Fluid Leak	2.35	4.07	7	5	1.58	0.22
9	11	Steering Linkage Condition	2.06	2.37	7	6	1.41	0.20
10	23A	Grease Leak at Brakes	1.66	2.56	4	3	1.49	0.00
11	30	Directional Light Intensity	1.55	1.55	3	3	1.41	0.14
12	27	Brake Adjustment Status	1.52	1.52	4	4	1.30	0.20
13	33	Directional Light Electrical	1.35	1.35	2	2	1.39	0.10
14	3	Ball Joint Condition	1.15	1.57	3	2	1.32	0.17
15	29A	Brake Pedal Overtravel	1.07	3.77	7	3	1.22	0.02
16	40A	Tire Overpressure	1.04	1.04	4	4	1.17	0.10
17	14	Steering Lubrication Status	0.95	0.95	2	2	1.29	0.00
18	22	Brake Fluid Reservoir	0.95	1.85	2	1	1.38	0.00
19	6	Suspension Bushing Condition	0.75	0.75	1	1	1.26	0.14
20	16A	Excess Steering Torque	0.60	1.17	2	1	1.18	0.02
21	29	Brake Temperature	0.45	0.45	1	1	1.10	0.45
22	29B	Brake Mechanical Operation	0.38	0.38	1	1	1.07	0.38
23	1	Wheel Bearing Condition	0.35	0.66	3	2	1.04	0.66
24	18	Headlight/Running Light Status	0.20	0.20	1	1	1.02	0.20
25	17	Headlight Aim	0.20	0.20	1	1	1.02	0.20
20	20	Other Light Status	0.15	0.15	1	1	1.01	0.00



28	BRAKE PERFORMANCE
40	TIRE PRESSURE (UNDERINFLATED)
37	BRAKE LIGHT INTENSITY
42	TIRE TREAD DEPTH
10	STEERING WHEEL PLAY
39	BRAKE LIGHT ELECTRICAL
21	BRAKE PAD AND LINING WEAR
23	BRAKE FLUID LEAK
11	STEERING LINKAGE CONDITION
23A	GREASE LEAK TO BRAKES
30	DIRECTIONAL LIGHT INTENSITY
27	BRAKE ADJUSTMENT STATUS
33	DIRECTIONAL LIGHT ELECTRICAL
3	BALL JOINT CONDITION
29A	BRAKE PEDAL OVERTRAVEL
40A	TIRE OVERPRESSURE
14	STEERING LUBRICATION STATUS
22	BRAKE FLUID RESERVOIR
6	SUSPENSION BUSHING CONDITION
16A	EXCESS STEERING TORQUE
29	BRAKE TEMPERATURE
29B	BRAKE MECHANICAL OPERATION
1	WHEEL BEARING CONDITION
18	HEADLIGHT/RUNNING LIGHT STATUS
17	HEADLIGHT AIM
20	OTHER LIGHT STATUS

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Figure 2–6 SENSOR AREA RANK ORDERING

4. Interactive effects (the presence of the Indiana PMVI program may affect vehicle condition in ways which are difficult to compensate for in extrapolating to a non-PMVI environment or to a different inspection system).

5. Technology (apparent and actual contradictions exist between the investigative data and laboratory experience).

6. Quality (correctness of judgments in specific cases).

Quantity

The Indiana sample is adequate to identify problem areas but not to establish definitively the magnitude of specific factors. Because the investigations performed on the program have dealt with the Level C cases, of which there are 420, it may be useful to analyze the accuracy of estimates based on a sample of this size.

The threshold of two accidents necessary to qualify a sensor area for further consideration corresponds to indictment in about one-half percent of all accidents investigated. Even if it were possible to establish accident causes unambiguously on a case-by-case basis, there is always a finite probability that a half percent contributor would be overlooked in a sample of finite size. For the sample at hand (420 cases) the probability that a half percent contributor would be identified zero times is 0.12, and 0.26 that it would be identified only once. Thus, for our limited sample size, there is a 38% chance that a half percent contributor would be overlooked.

This calculation is based on the unambiguous identification of causal factors. In practice, causal factors cannot be so identified. Rather, they appear at varying levels of certainty. This changes the probability of detection. Suppose, for example, a causal factor always presented itself at a 50% level of indictment, and that cases in which the factor was present could always be so identified.

In this instance, our half percent contributor would have to appear in a total of four cases to qualify for further consideration, but because of the ambiguity as to which half percent of all accidents it really caused, it would be detectable in a full one percent of all accidents. Calculating probabilities for this scenario, we find:

- a 1% chance that the factor appears in zero cases.
- a 6% chance that the factor appears in one case.
- a 13% chance that the factor appears in two cases.

- a 19% chance that the factor appears in three cases;

Totaling 49% chance that the factor appears in three or fewer cases.

Hence, there is an excellent chance that contributors of one half percent to the total accident picture will be overlooked if a cut-off of one half percent is used.

Let us now recalculate the numbers for a 1% contributor. Under the first scenario, in which defect indictment is unambiguous, we find:

- a 1.5% chance that no accidents are associated with the defect.
- a 6.2% chance that one accident is associated;

Totaling 7.7% chance that fewer than two accidents are found.

In the second scenario, the defect is detected twice as often (2%) but at the 50% indictment level. We then find (for a sample of 420):

- 0.02% chance that no such accidents are found.
- 0.18% chance that one such accident is found.
- 0.76% chance that two such accidents are found.
- 2.15% chance that three such accidents are found;

Totaling 3.11% that three or fewer such accidents are found.

Hence, the probability that a one percent contributor in the "real world" will fail to appear in one-half percent of the cases for a sample of 420 cases is rather low. That is, the important contributors (1% or more) almost certainly have been detected. Conversely, those contributors that appear to be important (i.e., appear frequently in the data) almost certainly are important, providing the sample is relevant, and the investigation methodology is sound. The marginal contributors, on the order of 1/2 to 1% are less well identified from a sample of this size.

Although the preceding calculations are illustrative only, they show the principles involved. The error analysis reported in Table 2-11 and shown in Figure 2-6 is based on the actual certainty distributions encountered in the Indiana Study. The error brackets in Figure 2-6 graphically illustrate the certainty associated with the Task 2 area identification. There is considerable overlap between the plus and minus one sigma bounds, indicating a marked uncertainty as to the precision of the rank ordering.

Currency

Phases II through V of the Indiana Tri-Level studies were performed in calendar years 1972 through 1975. However, the vehicles involved in defect related accidents were typically 6 to 7 years old, as shown in Figure 2-7. This figure omits total brake failures, the most current vehicle experiencing such a failure being a 1966 model. It is clear that FMVSS-105, which requires dual hydraulic systems on 1968 and later vehicles, would have replaced these total failures with partial failures, and would probably have eliminated the accidents altogether. It was for this reason that total brake failures of pre-68 cars were excluded from review in this study.

Inasmuch as it has not been possible to study 10 year old vehicles with dual hydraulic braking systems, it is not possible to evaluate accurately the role of partial hydraulic failures in the accident picture. Similarly, the impact of front disc brakes cannot be directly evaluated, because the population of cars with old disc brakes in this study is nowhere near today's level. Further developments in both brakes (FMVSS-105-75) and tires (radials, wider sections, etc.) are rendering the Indiana data still more outdated.

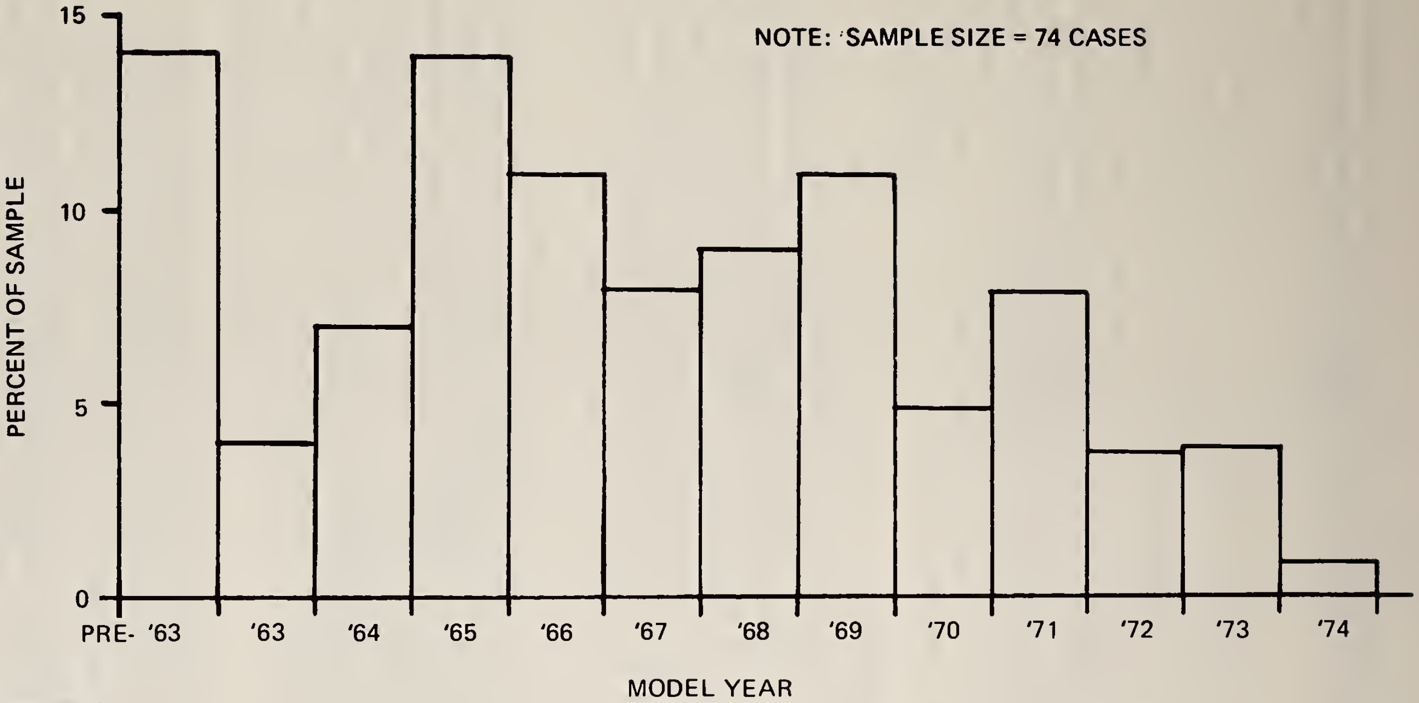
Generality

Some of the major limitations concern themselves with such important factors as topography, climate, and economic condition of vehicle owners.

The topography and climate of Indiana are certainly not representative of the nation and in fact are similar to these only in the relatively small region consisting of the state of Indiana and its immediate neighbors.

Perhaps the most important limitation pressed on this data base is that which describes the economic stratum occupied by the vehicle owner. There was no effort made to make a specific study in an urban area. The income level of the vehicle owners in the Indiana study is not representative of the economic status of the average driver.

Other objections have been raised as to the roads in the sample area (Monroe County has no interstate highways) and the coverage of the accident teams (lack of late evening coverage caused alcohol-related accidents to be undersampled). The requirement that involved drivers agree to participate in the study may have caused multi-car crashes to be undersampled. Finally certain cases could not be investigated because excess vehicle damage did not permit an accurate assessment of the pre-crash vehicle condition.



NOTE: SAMPLE SIZE = 74 CASES

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Figure 2–7 DISTRIBUTION OF MODEL YEAR IN INDIANA LEVEL C CASES REVIEWED FOR SENSOR APPLICATION

It will be necessary to conduct further research to determine the accuracy of the Indiana and other studies in representing the true condition of vehicles on a national basis. This research is clearly outside the scope of this program.

Interactive Effects

Indiana has an annual program of periodic motor vehicle inspection (PMVI). Until the effectiveness of the Indiana program is evaluated, it is difficult to determine the true incidence of defect related accidents. What limited information can be extracted from the IRPS study suggests that the Indiana inspection has low effectiveness on tire tread depth and steering wheel play. However, it is difficult to generalize from tenuous results such as these to other items (e.g., brake lights) examined within the Indiana system.

Technical Inconsistencies

The single most glaring technical inconsistency -- the tendency of the IRPS investigators to indict brake lining wear as a cause of abnormal brake performance, when the Bendix studies (Refs. 9, 10) discount this possibility -- may not be a deficiency in the data, but rather a contradiction arising from an attempt to read more into the (Bendix) test data than is warranted. This possibility is developed in detail in Section 3.2.7.1.

A further technical problem related to discrepancies that arise between the Level B (technician) and the Level C (in-depth) data as to the importance of specific vehicle defects. In certain areas (defective brake lights is one example) the observed percentage of accidents involving the same defect differs by more than a factor of ten. Inconsistencies of this magnitude, between studies conducted in the same county, by investigators from the same agency, are difficult to explain. Several possibilities are discussed in Section 3.1.1.1.

Quality of Judgment

Isolated cases can be found in which the investigator's report does not appear to justify the conclusions. One example involved a rear-end collision in which the conclusion was: defective brake light -- possibly causal. However, according to the report, the striking driver did not allege that the vehicle ahead was without brake lights, and the investigators could not determine whether the observed condition of defective lights was caused by crash damage. Further, the struck vehicle was equipped with a manual transmission and was stopped on level ground, so that there was no certainty that the brakes were even applied prior to the accident. In general, this probably means that the documentation rather than the judgment, is deficient. However, for a study of this type, in which heavy reliance is placed on the documentation errors of either type (documentation or judgment) add to the uncertainty of the determination as to sensor applicability.

It should be observed that most of the above mentioned limitations have been caused by conditions beyond the control of NHTSA and the Indiana personnel, and should not be construed as a criticism of either organization.

In summary, the Indiana data have been a useful source for the qualitative evaluation of sensor areas required in Task 2. In Task 3, which requires the use of quantitative methods, the subject of the Indiana data is re-opened.

2.2.2 Limit Performance

The second test of sensor candidacy is whether the sensor area can be shown to be important in limit maneuvering performance modes that are demonstrably important to accident prevention. In this context, limit performance refers to vehicle maneuvers attempted by an operator to avoid an impact or damage-producing excursion from the roadway. Such limit maneuvers primarily involve the processes of steering and braking, and includes the dynamic response of the vehicle, motion stability, and related considerations. Within the scope of the present program, therefore, the vehicle systems involved are brakes, steering, suspension, and tires.

The principal sources of data regarding the effects of various subsystems and components on the limit performance of vehicles are NHTSA sponsored studies by the Highway Safety Research Institute of the University of Michigan (Refs. 5, 6, 7) In these studies vehicles were tested in six extreme-type maneuvers with various induced degradations. This research concentrates on steering and suspension degradation, including tires, but several of the limit maneuvers involve concurrent braking under prescribed conditions. The major research effort, Reference 6 above, establishes the following:

> "The principal suspension component whose likely degradation can be shown to influence limit performance is the shock absorber."

Several other important conclusions are stated. Regarding general indeterminancies of the front wheel steer angle,

> "Indeterminancies...which arise due to lash in wheel bearings, ball joints, tie rod ends, or steering gear box, whether taken singly or in combination, do not exhibit a first order influence on vehicle limit performance."

As an observation impacting Task 2 objectives, Fancher, et al., concluded that,

> "Vehicle limit braking performance, both in straight line and curved path conditions, is more severely degraded by the presence of brake imbalance than by any of the steering and suspension component degradations examined."

Brake imbalance as a candidate sensor area has already been established by the analysis of accident data. The consideration of limit performance as a criterion introduces shock absorbers as an area not previously included from analysis of the accident data.

An additional remark, not really based on experimental results, by Fancher, et al., states,

> "Degradation categories in which limit performance sensitivity is felt to be pronounced include deterioration of tires and brakes -- it is felt that these data and other data clearly indicate the need for an examination of limit maneuvering properties as influenced by the level of normal tire wear and its distribution around the vehicle."

These concerns suggest that sensing of tire integrity should be considered as a candidate based on the possible significant influence of the tire integrity on limit performance maneuvers.

2.2.3 Failure Mode

The potential areas for sensor application listed in Table 2-12 are judged to relate to failure modes sufficiently critical that an accident situation could easily be created in the event of a failure.

Most of these areas for sensor application are in the suspension, steering, and brake subsystems.

Those conditions indicated with a * represent conditions that would be expected to disable a vehicle upon occurrence of a failure.

2.2.4 Failure Frequency

For each of the potential areas identified as having a critical failure mode, it was then required to evaluate the failure frequency to determine whether the area warranted further consideration. The definitions of failure adopted under this evaluation required a complete failure of the

TABLE 2–12. POTENTIAL SENSOR AREAS WITH CRITICAL FAILURE MODES

Wheel (spindle, steering knuckle) integrity	*
Ball joint/king pin condition	*
Spring condition	*
Fastener and bracket integrity	*
Wheel fastener	*
Steering fastener/bracket	*
Power steering fluid level/flow	
Power steering belt	
Steering torque	
Brake fluid reservoir level	*
Lubricant leak to brakes	
Brake drum/rotor integrity	*
Brake line integrity	*
Drum/rotor temperature	
Tire integrity	*

*Conditions whose failure would probably disable the vehicle.

component rather than a condition of degradation that could be labeled defective. If the definition is not applied in this manner, items such as ball joints would have qualified for further consideration. Because ball joint failures were neither major contributors to the accidents investigated in Indiana, nor to the vehicle disablement study (Ref. 8) summarized in Figure 2-8, it must be concluded that ball joint failure is not a major safety problem.

Using a strict definition of failure, it is possible to eliminate most items from further consideration. Of the items marked by stars in Table 2-12, only tire failure ranks as a significant contributor to vehicle disablement (Figure 2-8). Among the unstarred items, only lubricant leaks were near-qualifiers for further consideration under the accident data evaluation. Because lubricant leaks are seldom, if ever causes of vehicle disablement, it was determined that the evaluation under accident statistics constituted a fair evaluation, and lube leaks were not given further specific consideration. However, lubricant leaks leading to brake contamination are discussed in Section 3.2.8 (Brake Fluid Leak).

2.2.5 Consumer Benefit

Only one potential sensor area was able to qualify under the criterion of consumer benefits. This is principally because consumer benefit represents the last major test to be applied, and several sensors offering consumer benefits had qualified earlier. Another factor is the contract restriction in scope to only six areas -- brakes, tires, steering, suspension, lighting, and signaling. This excluded such items as fuel economy and emissions sensors from consideration. A final consideration was the magnitude of the benefit regarded as significant. For sensor concepts such as wheel bearings, or steering lube, early detection of a defect condition offers the potential of reduced repair/ costs and/or elimination of damage to the vehicle. However, these benefits were not judged to be significant, inasmuch as the current total dollar value of repairs in these areas is known to be small.

The one qualifying sensor area was front end alignment. Alignment is expensive to measure and adjust using currently available garage equipment. Moreover, the consequence of misadjustment, particularly in tire wear and fuel economy, can be significant.

2.2.6 Criteria 6 through 10

The first five of the screening criteria (discussed in subsections 2.2.1 through 2.2.5) serve the function of determining whether a potential candidate is worthy of additional consideration. The latter five criteria are used to determine whether the read-out mode is on-board or off-board. At this point, 11 candidate areas for sensor application

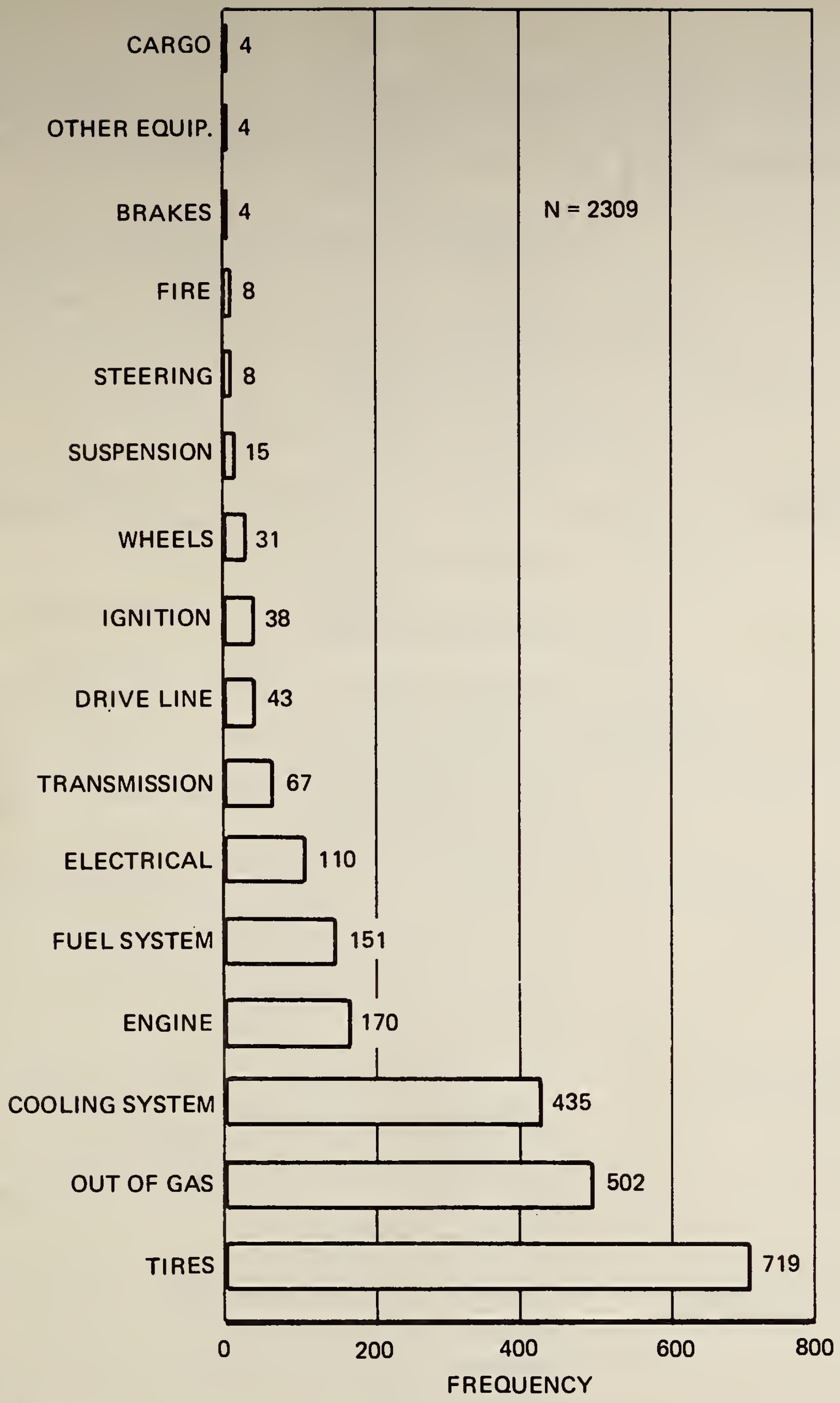

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Figure 2–8 DISABLEMENT DISTRIBUTION (Ref. 8)

have been identified. They are listed in Table 2-13, along with the modes of read-out selected. The underlying rationale for each sensor is described below:

Brake Performance -	Practical and clearly desirable to readout on-board (faults may develop at any time). Off-board possible. Possibly cheaper or superior to existing PMVI techniques. Readout Modes: Both.
Tire Pressure -	Practical and desirable to readout on-board (faults may develop at any time). Off-Board possible. Not commonly inspected via PMVI-needs more frequent checking. Readout Modes: On-Board only.
Brake Light - (Electrical or Optical)	Practical and desirable to readout on-board. Not superior to or cheaper than visual inspection for PMVI. Readout Mode: On-Board only.
Tire Tread Depth -	Not practical to readout on-board. Possibly superior PMVI technique. Readout Mode: Off-Board only.
Steering Wheel Play -	Practical to readout on-board but not superior to PMVI (Gradual degradation - periodic inspection adequate). Superior inspection as PMVI technique. Readout: Off-Board.
Pad and Lining Wear -	Practical on-board technique superior to PMVI. Possibly cheaper and better as PMVI technique. Readout Modes: Both.

Brake Fluid Leak -	Practical on-board technique - superior to PMVI. Possibly cheaper and better as periodic technique. Readout Modes: Both.
Shock Absorber -	Practical on-board technique - not superior to PMVI (gradual degradation). Possibly superior to existing PMVI techniques (manual inspection). Readout Mode: Off-Board.
Tire Integrity -	Not practical to provide on-board readout. Possibly superior to existing PMVI techniques. Readout Mode: Off-Board.
Front End Alignment -	Practical on-board technique - not superior to PMVI (gradual degradation). Possibly superior to existing PMVI techniques. Readout Mode: Off-Board.

The appropriate readout mode for each sensor is further discussed in Section 3.2.

TABLE 2—15. IDENTIFICATION OF CANDIDATE SENSOR AREAS

RESULTS OF SCREENING PROCESS	ACCIDENT STATS	LIMIT PERF.	FAILURE MODE	FAILURE FREQ.	CONSUMER BENEFIT	ON-BOARD READOUT PRAC	SUPERIOR TO PMVI	OFF-BOARD POSSIBLE	SUPERIOR INSP.	CHEAPER INSP.	CANDIDATE
SUSPENSION											
1 WHEEL BEARING'S CONDITION	N	N	N	-	N	-	-	-	-	-	
2 WHEEL (SPINDLE, STEERING KNUCKLE) INTEGRITY (FRONT ONLY)	N	N	Y	N	N	-	-	-	-	-	
3 BALL JOINT OR KING PIN CONDITION (FRONT ONLY)	N	N	Y	N	N	-	-	-	-	-	
4 SHOCK ABSORBER CONDITION	N	Y	-	-	-	Y	N	Y	Y	-	C
5 SPRING CONDITION	N	N	Y	N	N	-	-	-	-	-	
6 CONTROL ARMS AND STABILIZER BUSHINGS CONDITION	N	N	N	-	N	-	-	-	-	-	
7 FASTENER AND BRACKET INTEGRITY OR CONDITION	N	N	Y	N	N	-	-	-	-	-	
8 WHEEL FASTENER CONDITION	N	N	Y	N	N	-	-	-	-	-	
9 LUBRICATION STATUS	N	N	N	-	N	-	-	-	-	-	
STEERING											
10 STEERING WHEEL PLAY	Y	-	-	-	-	Y	N	Y	Y	-	C
11 LINKAGE INTEGRITY/CONDITION	N	N	N	-	N	-	-	-	-	-	
12 WHEEL ALIGNMENT (CASTER, CAMBER, TOE)	N	N	N	-	Y	Y	N	Y	Y	-	C
13 FASTENER AND BRACKET INTEGRITY OR CONDITION	N	N	Y	N	N	-	-	-	-	-	
14 LUBRICATION STATUS	N	N	N	-	N	N	-	Y	Y	-	
15 POWER STEERING FLUID LEVEL/FLUID FLOW	N	N	Y	N	N	-	-	-	-	-	
16 POWER STEERING BELT STATUS	N	N	Y	N	N	-	-	-	-	-	
16A EXCESS TORQUE	N	N	Y	N	N	-	-	-	-	-	
LIGHTING											
17 HEADLIGHT AIM	N	N	N	-	N	-	-	-	-	-	
18 HEADLIGHT AND RUNNING LIGHT STATUS (INTENSITY)	N	N	N	-	N	-	-	-	-	-	
19 LENS INTEGRITY	N	N	N	-	N	-	-	-	-	-	
20 CIRCUIT ELEMENT (RELAYS, SWITCHES, FUSE CIRCUIT BREAKER, WIRE, CONNECTORS) STATUS	N	N	N	-	N	-	-	-	-	-	
21 PAD AND LINING WEAR	Y	-	-	-	-	Y	Y	Y	Y	Y	C
22 RESERVOIR LEVEL	N	N	Y	N	N	-	-	-	-	-	
23 FLUID LEAK TO BRAKES	Y	-	-	-	-	Y	Y	Y	Y	Y	C
23A GREASE LEAK	N	N	Y	N	N	-	-	-	-	-	
24 DRUM/ROTOR INTEGRITY/STRENGTH	N	N	Y	N	N	-	-	-	-	-	
25 FLEX-LINE/RIGID LINE INTEGRITY	N	N	Y	N	N	-	-	-	-	-	
26 BRAKE FLUID CONTAMINATION (WATER)	N	N	N	-	N	-	-	-	-	-	
27 DRUM BRAKE ADJUSTMENT STATUS	N	N	N	-	N	-	-	-	-	-	
28 SYSTEM IMBALANCE	Y	Y	-	-	-	Y	Y	Y	Y	Y	C
29 ROTOR/DRUM TEMPERATURE	N	N	Y	N	N	-	-	-	-	-	
29A PEDAL OVERTRAVEL	N	N	Y	N	N	-	-	-	-	-	
29B LINKAGE OPERATION	N	N	N	-	N	-	-	-	-	-	
SIGNALING SYSTEMS											
TURN INDICATORS AND 4-WAY FLASHER											
30 LIGHT STATUS (INTENSITY)	N	N	N	-	N	-	-	-	-	-	
31 FLASH RATE	N	N	N	-	N	-	-	-	-	-	
32 CANCELLATION STATUS	N	N	N	-	N	-	-	-	-	-	
33 CIRCUIT ELEMENT STATUS	N	N	N	-	N	-	-	-	-	-	
34 LENS INTEGRITY	N	N	N	-	N	-	-	-	-	-	
HORN											
35 ONE HORN FAILURE IN DUAL HORN SYSTEM	N	N	N	-	N	-	-	-	-	-	
36 CIRCUIT ELEMENT STATUS	N	N	N	-	N	-	-	-	-	-	
BRAKE LIGHTS											
37 LIGHT STATUS (INTENSITY)	Y	-	-	-	-	Y	Y	Y	N	N	C
38 LENS INTEGRITY	N	N	N	-	N	-	-	-	-	-	
39 CIRCUIT ELEMENT STATUS (ELECTRICAL)	Y	-	-	-	-	Y	Y	Y	N	N	C
TIRES											
40 TIRE PRESSURE (UNDER INFLATED)	Y	-	-	-	-	Y	Y	Y	N	N	C
40A TIRE PRESSURE (OVER INFLATED)	N	N	N	-	N	-	-	-	-	-	
41 TIRE INTEGRITY	N	-	Y	Y	-	N	-	Y	Y	-	C
42 TREAD DEPTH	Y	-	-	-	-	N	-	Y	Y	-	C
43 WEAR PATTERN	N	N	N	-	N	-	-	-	-	-	

N = NO
Y = YES
C = CANDIDATE

2.3 SUMMARY OF RESULTS

The evaluation of potential candidate sensor areas can be summarized in a few tables. For each of the potential sensor areas listed in Table 2-1, Table 2-13 shows how the sensor fared in application of the 10 evaluation criteria. Dashes in the table indicate that the corresponding test was not applied, because the outcome of a prior test permitted it to be by-passed. Based on these criteria, Table 2-14 lists the candidate sensor areas considered in Task 3 from an implementation viewpoint. As a generalization on the outcome of the process, it may be stated that the justification for the sensor areas which qualified on the basis of Criteria 2 through 5 (failure criticality, etc.) is a good deal weaker than for those qualifying based on Criterion 1, (accident investigation).

TABLE 2–14. SENSOR AREAS AND READOUT MODES FOR FURTHER CONSIDERATION IN TASK 3

Sensor and index	Readout mode
1. Brake performance (28)	Both
2. Tire pressure (40)	On-board
3. Brake light intensity (37)	On-board
4. Tire tread depth (42)	Off-board
5. Steering wheel play (10)	Off-board
6. Brake light electrical (39)	On-board
7. Brake pad & lining wear (21)	Both
8. Brake fluid leak (23)	Both
9. Shock absorber (4)	Off-board
10. Tire integrity (41)	Off-board
11. Alignment (12)	Off-board

3.0 SENSOR IDENTIFICATION (TASK 3)

The requirements of this task were:

"For the selected areas determined in Task 2, identify all existing sensor techniques or hardware. For those areas not currently covered by sensor technology, develop appropriate sensor techniques. Existing techniques should be reviewed for possible improvement. This portion of the task shall require the formulation and weighting of objectively defined evaluation criteria. . .The new techniques shall be developed to the point that sufficient information is available to conduct the evaluation. . .supply supporting data and discussion in the areas of

a. Reliability and life cycle costs.

b. Potential benefits.

c. Sensor design.

d. Inspection equipment and manpower requirements.

e. Public response and acceptance.

f. Existing procedures for candidate areas.

g. Tradeoff between improved component design, complete off-vehicle inspection without sensors, periodic off-vehicle inspection using sensors, and continuous on-board monitoring.

h. Display techniques (on-board sensor systems).

i. Off-vehicle readout and interface."

At NHTSA direction, and with Avco's concurrence, this evaluation has taken the form of a cost-benefit analysis for each of the candiate sensor areas. This means that each sensor has been evaluated quantitively, rather than qualitatively, as in Task 2.

As a result, the evaluation of sensor areas performed under this task has been both broader in scope and sharper in focus than that performed in Task 2. In addition to looking at the role of defects in accidents involving vehicles as they exist today, this task has required performance evaluations of devices not currently available. The initial cost of the sensor and other economic impacts have been considered. Alternative countermeasures have also been considered.

3.1 METHODOLOGY AND OVERVIEW

The use of cost-benefit analysis to justify (or disqualify) safety measures is a controversial subject. In its 1972 report, Societal Costs of Motor Vehicle Accidents, (Ref. 11) NHTSA states:

> "...we are not arguing that it is unwise to spend more than the amounts calculated...We have provided an estimate of some of the quantifiable losses in societal welfare resulting from a fatality and can only hope that this estimate is not construed as some type of basis for determining the 'optimal' (or even worse, the 'maximum') amount of expenditure to be allocated to saving lives."

However, it is necessary to adopt a finite value on human life if only to choose between competing life-saving countermeasures. An updated version of the numbers calculated by NHTSA has been used as representative. An important point to remember is that cost-benefit analysis is largely parmetric in nature; i.e., it explores the consequences of a set of assumptions, which the reader/reviewer is free to revise at any time.

The purpose of this section is to state these assumptions, plus other groundrules and limitations whose understanding is necessary to proper interpretation of the results. It must be stated at the beginning that neither the costs nor the benefits of many on-board sensor concepts can be estimated with great precision using available data. Indeed, the question of whether benefits exceed costs cannot be definitively resolved for several of the sensor concepts.

The cost benefit methodology and overview presented in this section is organized into three major parts. The first part develops a potential benefit in both safety and economic areas for each of the candidate sensor areas. These estimates are developed "from the top down"; that is, they are derived by progressively partioning macro-statistics until the desired level is reached.

The second part of this section develops the groundrules for cost estimates. Sensor cost estimates are developed "from the bottom up". They are obtained from micro-scale data on the costs of components, which is then integrated to produce the final estimate. The application of these groundrules to specific sensors is deferred until Section 3.2. Other alternatives, such as periodic inspection, have been analyzed using a "top-down" approach.

The third part of this section develops the groundrules for analyzing the effectiveness of on-board sensors in providing the benefits postulated in each candidate area. Although some very broad bounds are developed, the results in this area are so tentative that the basic approach to presenting results in parametric. That is, the outcome of the analysis is stated as a function of effectiveness.

3.1.1 Potential Benefits

3.1.1.1 Reduction in Accident Costs

For purposes of this report, an updated version of the original NHTSA reference on the cost of motor vehicle accidents has been prepared. This estimate is based on Federal Highway Administration and National Safety Council figures for motor vehicle accidents in 1974. U.S. Department of Labor price indices for general goods, medical care, and automobile services have been used to account for inflation between the years 1971 (the baseline year of Reference 11), and 1975. The calculations are illustrated in Table 3-1.

TABLE 3–1. THE DOLLAR VALUE OF ACCIDENTS COMPUTED FROM STANDARD REFERENCES

	Number[1]	Value per[2]	Inflation[3]	Item total
Fatalities	46.049K	$200.7K	1.322	$12.22B
Injuries	2.653K	$ 7.3K	1.307	$25.32B
Property damage	14.4M	$500.	1.022	$ 8.03B
		Total		$45.52B

Divided by number of registered vehicles (135.7M) = $336/(Veh Year)

[1] Federal Highway and National Safety Council, 1974.

[2] NHTSA; Societal costs of motor vehicle accidents, 1972.

[3] U.S. Dept. of Labor, 1971-1975.

There are several points worthy of mention in this calculation. First, the calculations are based on all motor vehicle accidents. Clearly, it is inappropriate to base the analysis on passenger car occupant statistics only, because pedestrians, cyclists, and occupants of trucks and busses may also be killed on injured by a defective automobile. In order to evaluate onboard vehicle sensors for passenger cars, it is preferred to have statistics which relate only to accidents in which passenger cars were involved; however, the available references are somewhat ambiguous and it is not clear whether these figures are readily available. An estimate based on all motor vehicles may be slightly conservative for passenger cars since large trucks and busses have a better safety record than privately owned cars. However, the methodological problem of how to define properly the universe of vehicles and accidents under consideration is minor compared to other problems contributing to variations in the total societal cost of accidents.

Table 3-2 shows several other estimates of the societal cost of accidents. Collectively these estimates differ by more than a factor of two. The difference between the RECAT estimate and the others is principally due to a lower societal economic loss associated with loss of life. The effect of inflation on the 1974 estimates have been moderated by the reduction in highway deaths accompanying the gasoline shortage and the introduction of the 55 MPH speed limit.

TABLE 3–2. SOCIETAL COST OF ACCIDENTS – A COMPARATIVE SUMMARY OF ESTIMATES

Source	Ref	Base year	Societal cost (Billions)	Cost per vehicle year	Number of vehicles (Millions)
RECAT	(12)	1971	$18.7	$170.	110.
DOT (NHTSA)	(11)	1971	$45.7	$352.	129.8
DOT (NHTSA)	(13)	1973	$26.5	$263.	100.8*
(This report)		1974	$45.6**	$336.	135.7

*Passenger cars only
**1974 Accidents, 1975 dollars

Some more recent NHTSA reports also contain useful comparative data on the total cost of accidents. A recent release from the Secretary of Transportation (Reference 14) contains a detailed analysis of injury costs using the abbreviated injury severity scale (AIS). This analysis leads to a societal cost of $11.2 billion for injuries (including fatalities) to passenger car occupants.* This total is almost exactly one-third of the societal cost computed by this analysis (which includes all motor vehicle accidents). Despite valuing a fatality as a loss to society of $286K (larger than the number used here) the distribution of injury severities is such that the average cost of a non-fatal injury is only $1266 in the Secretary's analysis, as compared to $9540 in this analysis. Because this analysis is based on an earlier NHTSA reference, it may be that the lower injury cost is more representative of current DOT thinking.

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*The baseline year of the calculation is not stated. However, the number of passenger car occupant fatalities used is 27,200.

Closer agreement between old and new NHTSA estimates can be found in Reference 15 which places the value of property damaged in auto accidents at $8 billion for 1975. However, this report also indicates that damage in unreported accidents may be comparable to the total for reported accidents.

Having a total cost of accidents, the next stop is to subdivide this cost into the respective contributions from various vehicle causes. This process has proven exceedingly difficult, using data currently available. The classical approach is to determine the fraction of all accidents attributable to defects in each subsystem and to distribute the total cost of accidents according to these fractions, which are known as the "safety criticalities" of the various defects. In its simplest form, this approach assumes that defect related accidents have the same costs as non-defect-related accidents. Alternatively, one can include weighting factors for accident severity and thereby obtain a better picture of the accident cost of vehicle defects. Within the current state of the art, however, there is little evidence on the relative severity of defect-related and non-defect related accidents. Within this report, therefore, weighting factors for severity will not be used.

There are two generic approaches to the determination of safety criticality -- the direct experimental approach (exemplified by the Indiana study) and the analytical approach (exemplified by the Booz-Allen safety criticality analysis). Neither approach has been systematically and fully exploited in any recent studies known to Avco. As a result, the data base on safety criticality is quite weak.

To illustrate the problems that can arise, a total of four safety criticality estimates have been prepared -- three based on the same set of experimental data, and a fourth based on subjective interpretation of all available data, with extrapolation to the conditions of interest -- current vehicles, non-PMVI environment and nationally representative driving conditions. These estimates exhibit substantial variation.

Experimental Results

The standard (indeed, the only) experimental reference on the role of vehicle defects in accident causation is the Indiana case study previously discussed in Section 2.1 of this volume. These studies have, upon occasion, been mis-used in a way which suggests that the role of vehicle defects is considerably larger than the study actually indicates. The statement that vehicle factors were cited as "possibly causal" in 12.6% of the Indiana Level C cases is not equivalent to a statement that vehicle factors might possibly cause 12.6% of all accidents. The difference between these statements, although subtle, is of considerable importance.

The mathematics are easily illustrated by example. Suppose, for simplicity, that a particular level of indictment is equivalent to a 50-50 chance that a particular accident was caused by the factor in question. Then, if a specific vehicle factor is cited 100 times in 1000 investigations as a 50% causal factor, the probability that this factor was, in fact, causal in all 100 cases is $(0.5)^{100}$ or 7.9×10^{-31}. This is a vanishingly small number. A far better estimate of the importance of this factor is obtained by assuming that it was, in fact, causal in 50 of the cases and not causal in the other 50. In other words, the number of times that a factor is cited should be multiplied by the strength of the indictment (expressed as a probability) to obtain the expected number of times that the factor is actually causal. In addition, factors indicted as severity-increasing, rather than causal, can be accommodated by asserting an equivalence between two accidents reduced in severity and one accident totally eliminated. The various levels of indictment employed in the Indiana study can now be combined using a simple formula:

$$SC = \frac{1}{N}(0.95\ (N_{CC} + 1/2\ N_{CSI}) + 0.80\ (N_{PrC} + 1/2\ N_{PrSI}) + 0.40\ (N_{PoC} + 1/2\ N_{PoSI}))$$

where

SC = Safety criticality

N = No. of cases investigated (420 for Level C, about 2265 for Level B)

N_{CC} = No. of cases judged Certain-Causal

N_{CSI} = No. of cases judged Certain-Severity Increasing

N_{PrC} = No. of cases judged Probable-Causal

N_{PrSI} = No. of cases judged Probable-Severity Increasing

N_{PoC} = No. of cased judged Possible-Causal

N_{PoSI} = No. of cases judged Possible-Severity Increasing.

Use of this formula implies that, over a large number of cases, indictments labeled certain will average to about 0.95 probability; that those labeled probable to 0.80; and possible to 0.40.* Of course, in specific cases, there is no constraint that the causal probability be any one of these three numbers - probabilities are free to assume any value between zero and one.

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*A recent review of several Indiana cases in which comparisons were made between the three levels of indictment and the numerical probability estimates indicated the following correspondence: Certain = 0.90, Probable = 0.73, Possible = 0.43.

In recognition of this, the Indiana investigators began (in Phases IV) and V) to make numerical probability estimates consistent with their certain-probable-possible hierarchy, and to publish these estimates along with their reports. Use of this numerical estimate has a clear advantage over the formula given previously for estimating the safety criticalities when the number of case samples is small. Rather than assume that two indictments at the possible level average 0.40 in probability, it is possible to sum the probability estimates and compute the average directly. Indeed, since the average probability is multiplied by the number of cases to produce an expected number of actual cases, one can simply sum the probabilities to obtain the same result and avoid the division step altogether.

After all this discussion, we find that there are two methods available for computing safety criticality, which may be used to develop three different estimates from the Indiana data. The combinational formula may be applied to either the Level B or Level C data, and the case-by-case analyses (Level C only) may be compiled separately and then converted to percentages. The results obtained by applying these procedures are listed in Table 3-3. The estimates developed through case-by-case review are based on the reviews described in Section 2.2. However, the entries used are the indictment totals for all cases, rather than unaware cases only. (Discussion of this table is provided later in this section.) Each of the first estimates in Table 3-3 is subject to the limitations of the overall Indiana program - design of vehicles investigated, the influence of the Indiana PMVI program, limited sample size, and the one-region environment. (For a further discussion of these factors, the reader is referred to Section 2.2.1.4 of this report.)

Analytical Approaches

An alternative to the pure experimental approach is the use of analytical techniques in conjunction with experimental data. The earliest known attempt to develop safety criticality information using analytical techniques was reported by Booz-Allen Applied Research in 1970 (Ref. 17). However, these estimates are unusable. The principal difficulty appears to be non-discrimination between potential causes of failure and actual failures. For example, fuel system defects that might lead to vehicle fires were evaluated as if they were certain to eventually cause a fire.

A more recent analytical attempt to define safety criticalities is described below. Like the Booz-Allen work, a key element is the use of "expert opinion" to establish estimates for a set of "unmeasurable" quantities.

However, in the present case, the quantities estimated were the "true" apportionments of defect related accidents among various causes. The consultants (Treat and Oldham) were asked to base their estimates on all

TABLE 3–3. SAFETY CRITICALITY ESTIMATES VARY WIDELY

Candidate areas	Experimental Methods			Analytical Methods
	Indiana Level B	Indiana Level C	Review of Level C	Consultant estimate
Brake performance	3.03(1)	5.40(1)	2.48	3.19
Tire pressure	0.18	1.92	1.51	0.97
Tire tread	1.63	2.45	1.67	1.13
Brake lite intensity	0.06	0.57	0.84	0.12
Brake lite electrical	0.06	0.57	0.72	0.12
Brake pad contam via fluid	(2)	(2)	0.89	(4)
Steering play	0.78	1.27	1.00	0.26
Pad and lining wear	(2)	(2)	1.15	(4)
Shock absorber	0.19	0.00	0.00	0.23
Front end alignment	(3)	(3)	0.00	0.05
Tire integrity	0.09	0.00	0.00	0.10

(1) Brake performance problems not segrated into pre and post 1968 cars, total is for brake system problems on all vehicles in study.

(2) Not identified as specific fault - combined with other ratings.

(3) Not included in classification scheme.

(4) Detailed breakdown of brake system faults not performed.

information at their disposal (including Indiana), but were not allowed the use of written reference materials.

The hierarchical structure underlying the estimation process is illustrated in Figures 3-1 and 3-2. This structure is similar to that employed by Indiana (Ref. 16) but was developed independently. The numbers alongside (or within) each balloon represent the safety criticality estimates, expressed as a decimal fraction. This procedure was pursued to the depth necessary to develop safety criticality estimates for the sensors listed in Table 2-14. The results of these indepth evaluations are listed in the fourth column of Table 3-3.

Comparison of Estimates

Referring to Table 3-3, which compares three experimentally determined safety criticalities (all generated from the same basic data) with the consultant estimates, it is clear that substantial differences exist. Some of these differences can be attributed to chance. In a small sample, the actual count of accidents of any specific type is subject to considerable random variation. Other differences are almost certainly the result of other factors.

Consider, for example, the ten-to-one difference between the safety criticality of brake lights as determined in Levels B and C. The discrepancy between the Level B and C results is an extreme example of a systematic tendency for the Level C investigations to indict vehicle defects more often than in Level B cases. This tendency is understandable in view of the more thorough vehicle examination performed in Level C. However, in areas such as brake lights, it is conceivable that the in-depth investigators have over-stated their indictments. This interpretation is supported by the results of the Avco reviews of the Level C cases, which have generally reduced the strength of the indictment relative to the assigned weighting factors of 0.95, 0.80 and 0.40.

Societal Costs in Specific Sensor Areas

Having developed a set of safety criticality estimates, (expressed as decimal fractions, rather than percentages) the conversion to accident cost in each candidate area is accomplished by multiplying the safety criticality estimates and the total societal cost. Rather than annual societal totals or costs per vehicle year, we have used lifetime cost per vehicle, assuming a 12-year vehicle life. The value of 12 years for the useful vehicle life represents the largest estimates appearing in various sources, and does not consider such factors as the net present values of future accidents, and the true distribution of accident exposure throughout the vehicle life. As such, it may overstate the cost of accidents.

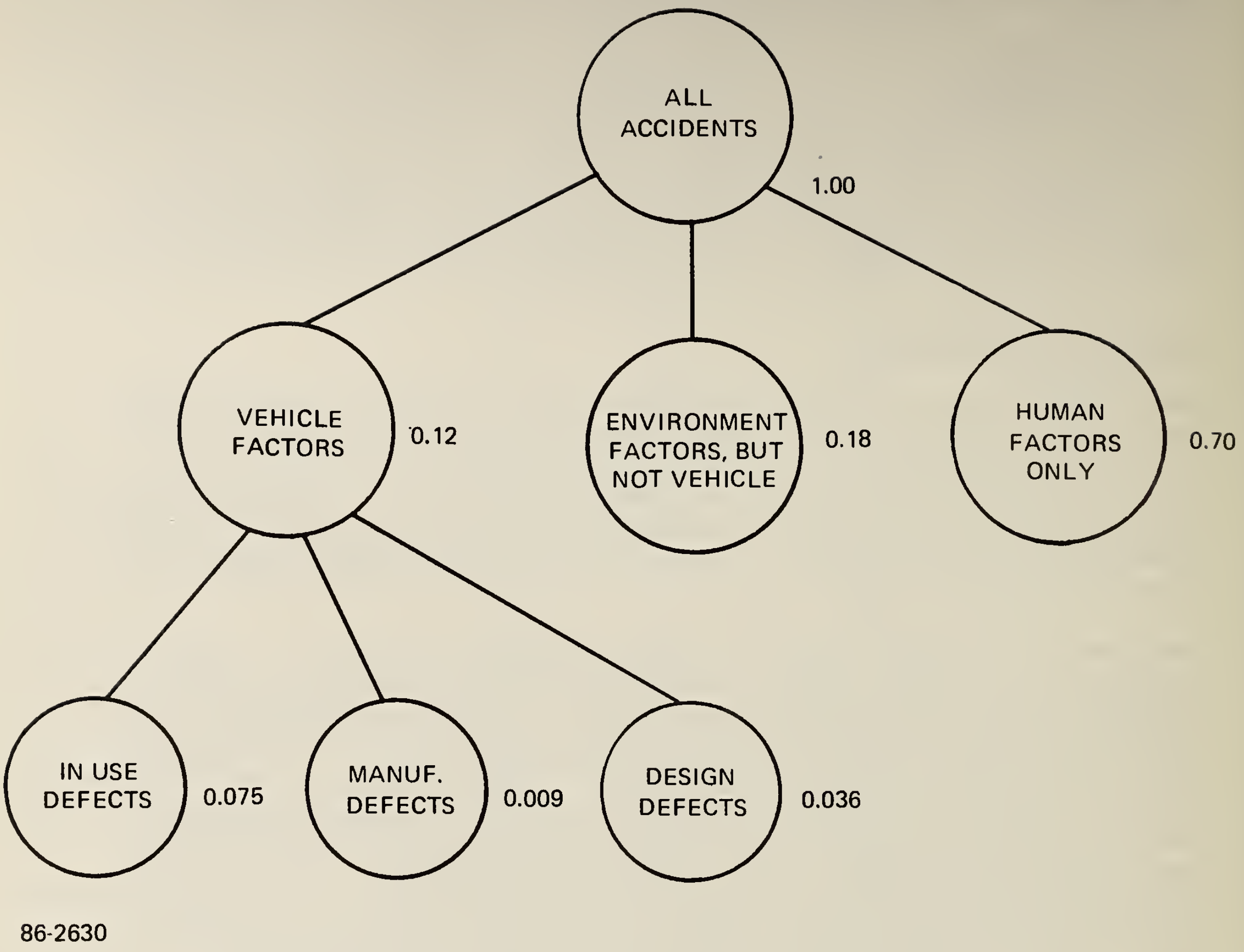
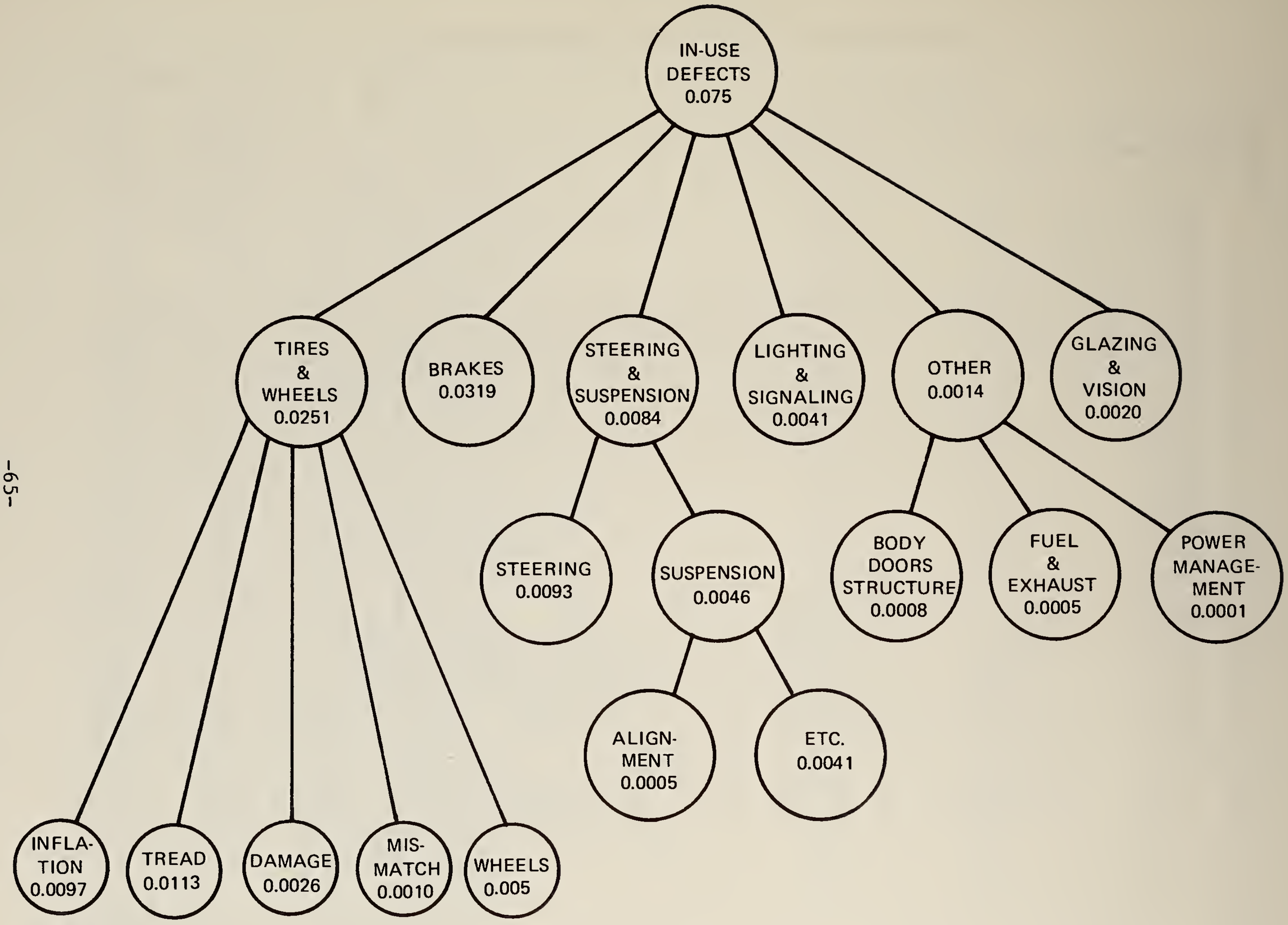


Figure 3–1 TREE STRUCTURE USED TO DEVELOP SAFETY CRITICALITY ESTIMATES



86-2631

Figure 3–2 HIGH LEVEL TREE STRUCTURE FOR IN-USE DEFECTS

Using this value, in conjunction with the fourth of the safety criticality estimates presented earlier, we obtain Table 3-4.

TABLE 3–4. LIFETIME ACCIDENT COSTS DERIVED FROM SAFETY CRITICALITY

	Accident cost $/vehicle lifetime
Brake performance	$128.62
Tire pressure	39.11
Tire tread	45.56
Brake light intensity	4.84
Brake light electrical	4.84
Brake fluid leak	40.72
Steering play	10.48
Pad and lining wear	45.96
Shock absorber	9.27
Front end alignment	2.02
Tire integrity	4.03

It is interesting to compare the numbers in this table with the corresponding maximum impacts computed on the basis of Task 2 information, including sensor areas not specifically examined in Task 3. To make this comparison, we have expressed the indictment total for unaware cases (Table 2-11) as a percentage by dividing them by the total number of cases (420), and them multiplied by the lifetime cost of accidents ($4032). The results are shown in Table 3-5. It can be seen that the maximum safety impact of several non-qualifying sensors exceeds that of the three sensors included on the basis of non-accident data considerations. Inasmuch as the safety impact estimates for these candiate areas are partially based on the Indiana results, it is not surprising that some nearly-qualifying sensors have a greater potential impact than those promoted for consideration on a more subjective basis. However, to the extent that the safety impact estimates are independent of the Indiana data, it is encouraging to find that expert opinion has corroborated the Indiana investigative findings.

TABLE 3–5. MAXIMUM SENSOR SAFETY BENEFIT AS BASED ON TASK 2

Rank	Sensor number	Description	Indictment total: Unaware cases	Indictment total: % of cases	Car lifetime safety benefit
1	28	Brake performance	6.84	1.63	65.73
2	40	Tire pressure (underinflated)	6.36	1.54	62.10
3	37	Brake light intensity	3.54	0.85	34.28
4	42	Tire tread depth	3.52	0.84	33.87
5	10	Steering wheel play	3.46	0.83	33.47
6	39	Brake light electrical	3.04	0.73	29.44
7	21	Brake pad and lining wear	2.82	0.68	27.42
8	23	Brake fluid leak	2.35	0.56	22.58
9	11	Steering linkage condition	2.06	0.49	19.76
10	23A	Grease leak at brakes	1.66	0.40	16.13
11	30	Directional light intensity	1.55	0.37	14.92
12	27	Brake adjustment status	1.52	0.37	14.92
13	33	Directional light electrical	1.35	0.33	13.31
14	3	Ball joint condition	1.15	0.28	11.29
15	29A	Brake pedal overtravel	1.07	0.26	10.49
16	40A	Tire overpressure	1.04	0.25	10.08
17	14	Steering lubrication status	0.95	0.23	9.28
18	22	Brake fluid reservoir	0.95	0.23	9.28
19	6	Suspension bushing condition	0.75	0.18	7.26
20	16A	Excess steering torque	0.60	0.15	6.05
21	29	Brake temperature	0.45	0.11	4.44
22	29B	Brake mechanical operation	0.38	0.09	3.63
23	1	Wheel bearing condition	0.35	0.09	3.63
24	18	Headlight/running light status	0.20	0.05	2.02
25	17	Headlight aim	0.20	0.05	2.02
26	20	Other light status	0.15	0.04	1.62

3.1.1.2 Potential Economic Benefits

Estimates of economic benefit have been developed in two general areas -- tires and brakes. Tire benefits included reduced wear, improved gas mileage, and reduced failures (blowouts). Brake benefits include reduced drum/rotor refinishing and reduced drum/rotor replacement. These are cited, as appropriate, in the specific sensor discussions, Sections 3.2.1 through 3.2.11.

Tires

The following items are of interest: the potential fuel savings associated with underinflated tires, the tread wear associated with underinflation and misalignment, and the frequency of tire failures associated with both underinflation and tire faults.

The potential fuel consumption impact can be estimated in a straightforward manner. Figures 3-3 and 3-4 show published curves of fuel-economy vs. inflation pressure for constant speed tests and different tire constructions. The second of these indicates that a change of 10 psi (from 36 to 26) is worth about 5% in fuel efficiency for tires of conventional construction. Because fuel economy changes of this magnitude are difficult to measure accurately, and results may be somewhat test-specific, it is useful to see how this number can be derived without recourse to actual fuel consumption tests.

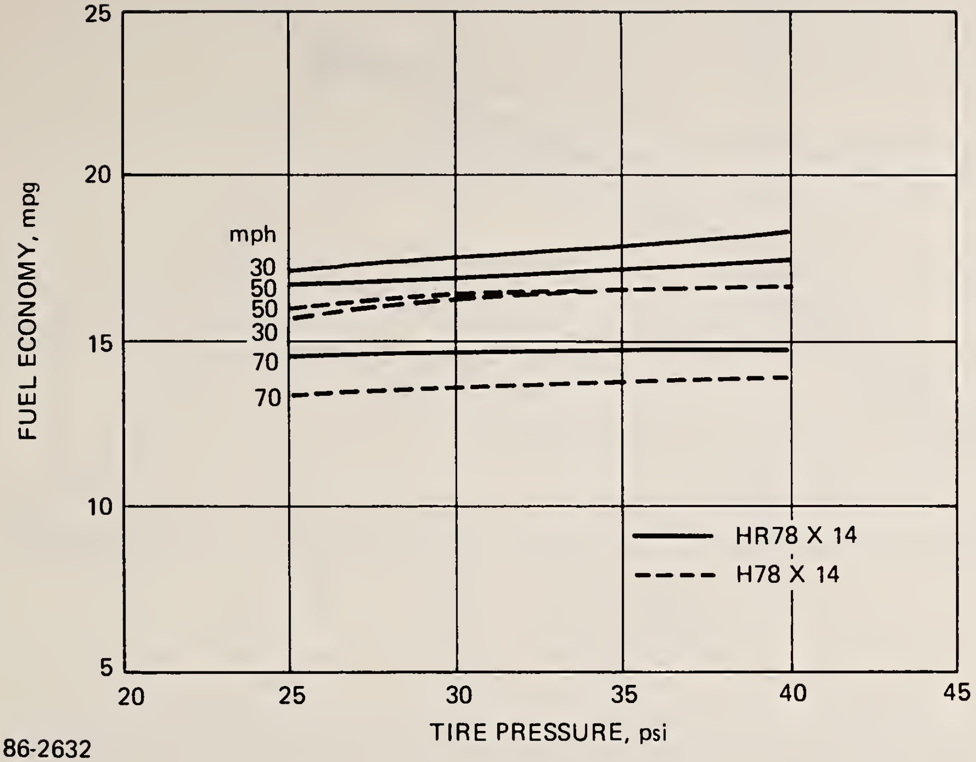
Figures 3-5 and 3-6 show tire rolling resistance under varying conditions of speed and pressure. A generalization of these results would be that a 10 psi change in pressure is worth about 20% in rolling resistance. Because rolling resistance is about 25% of the energy required to traverse the EPA composite city-highway cycle (Figure 3-7), we again obtain a 5% fuel usage change for a 10 psi change in pressure.

To arrive at a lifetime fuel savings for properly inflated tires, it is necessary to invoke the results of tire inflation surveys. If we take the surveys to indicate that one tire in four on one car in four is 5 psi low, the impact of an inflation sensor is computed as follows:

$$\frac{1/2\% \text{ Fuel Usage}}{1 \text{ psi on all 4 tires}} \times \frac{1 \text{ tire}}{4 \text{ per car}} \times \frac{1 \text{ car}}{4 \text{ cars}} \times 5 \text{ psi} = \begin{array}{c} 0.156\% \\ \text{fuel usage} \end{array}$$

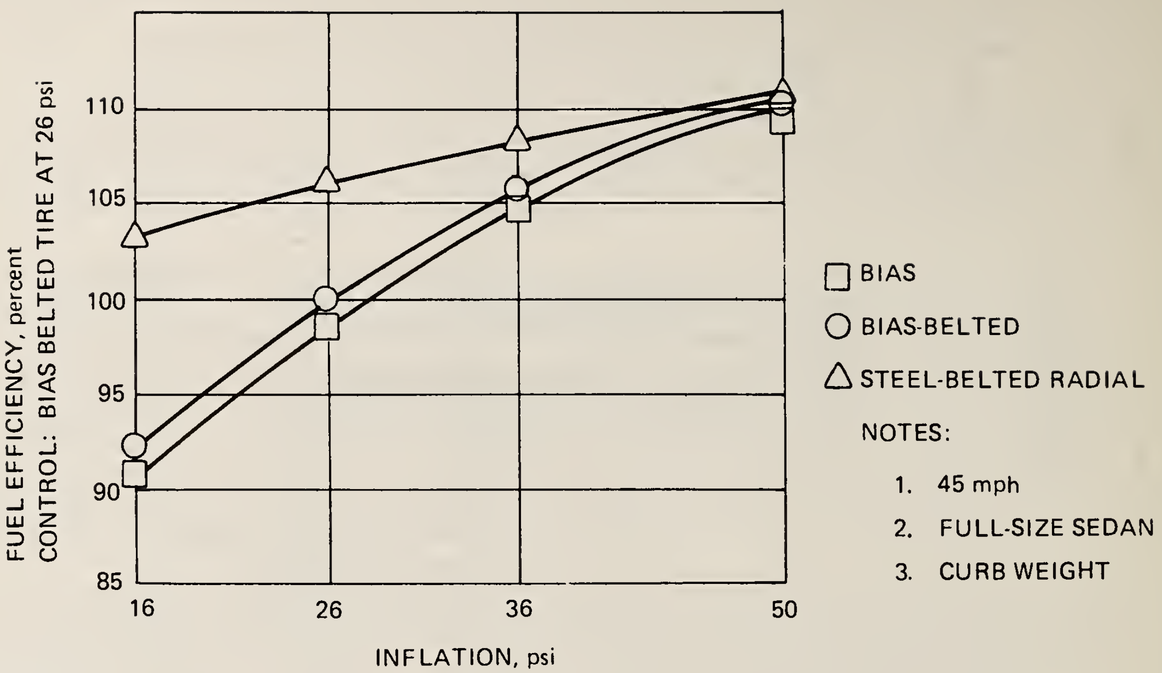
At 5¢/mile (12 mpg, 60¢/gallon) 100,000 miles represents $5,000 worth of fuel. Sixteen hundredths of one percent of this number is $8.00.

Cost savings from reduced tread wear is much more difficult to estimate than savings from improved mileage because of the relative lack of definitive data relating accelerated wear to underinflation. One underinflation warning sensor developer claims that "underinflation is the



86-2632

Figure 3–3 VEHICLE TEST FUEL "ECONOMY" VS STABILIZED TIRE PRESSURE FOR RADIAL HR-78-14 AND BIAS-BELTED H 78-14 TIRES (Ref. 20)



86-2633

Figure 3–4 RELATIVE FUEL EFFICIENCY VS DEFLATION PRESSURE FOR THREE TYPES OF TIRES (Ref. 18)

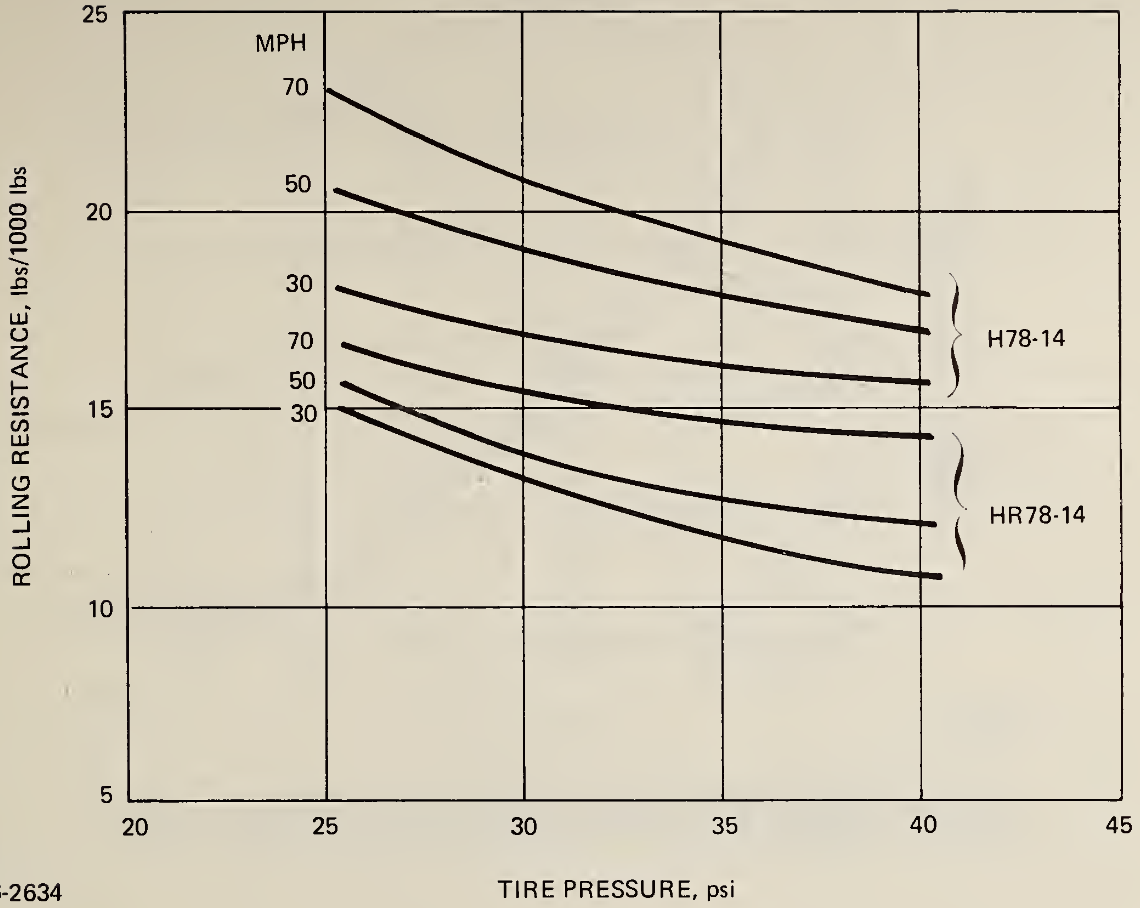


Figure 3–5 TIRE ROLLING RESISTANCE VS STABILIZED TIRE PRESSURE FOR RADIAL HR-78-14 AND BIAS-BELTED H 78-14 TIRES (Ref. 20)

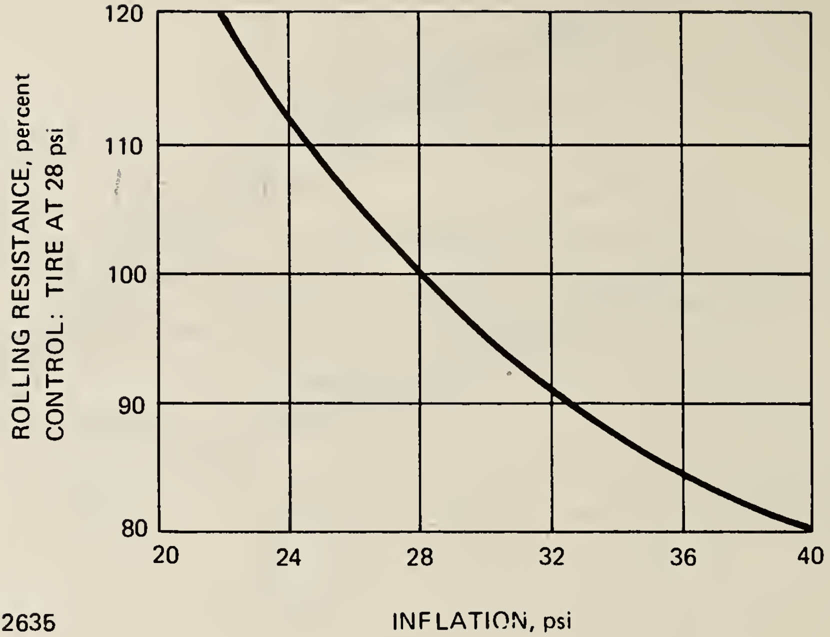
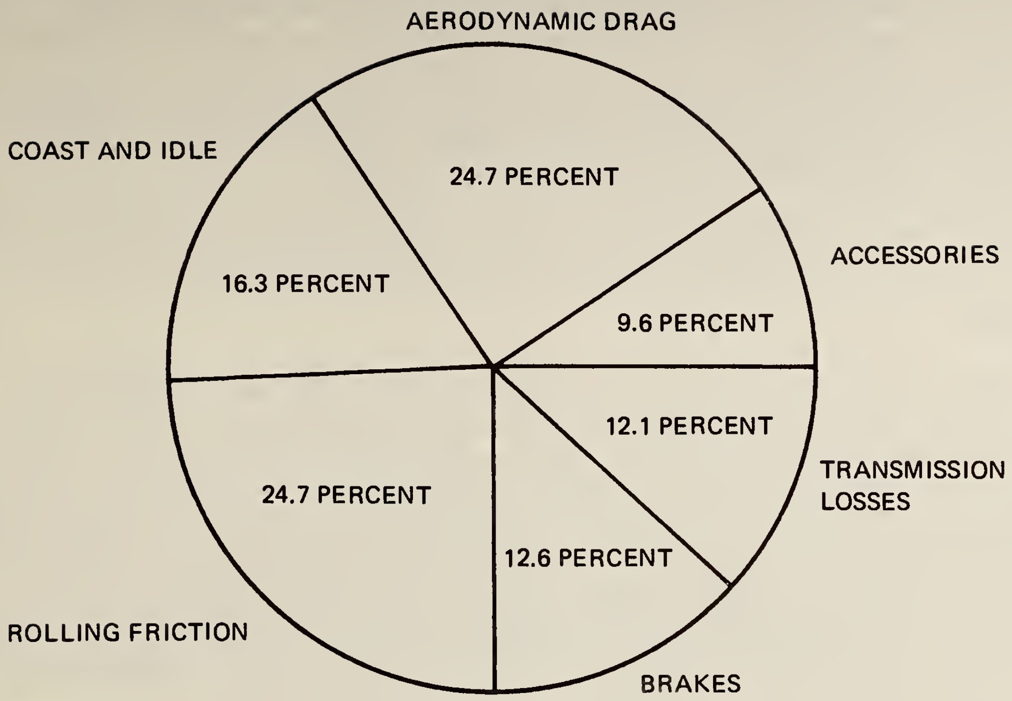


Figure 3–6 EFFECT OF INFLATION PRESSURE ON ROLLING RESISTANCE (Ref. 18)



86-2636

Figure 3—7 DIVISION OF ENERGY REQUIREMENTS IS SHOWN FOR A 3,500 POUND AUTOMOBILE WHEN OPERATED ON THE EPA COMPOSITE CITY-HIGHWAY TEST CYCLE

largest contributor to tire wear. Five pounds of underinflation reduces tire life by 32%; six pounds of underinflation reduces tire life by 38% and nine pounds of underinflation reduces tire life by 52%." Unfortunately these statistics cannot be substantiated but, if the numbers are taken at face value and if the prior assumption that one tire in four on one car is four is 5 psi underinflated then it follows that one tire in 16 is worn approximately one third faster than normal. On a basis of approximately 1.5 tires consumed per automobile per year. (Per Ref. 22) 40 million tires were delivered with new U.S. manufactured cars in 1975 while 130 million replacement tires were sold. This is approximately 1.5 tires per year for some 110 million U.S. automobiles - ignoring foreign made tires marketed in the U.S.)

The tire loss per automobile per year would equal 32% x 1/16 x 1.5 = 3% of 1 tire. At an average cost to the consumer of $40 per tire this would equal approximately $1.20 per car per year of $14.40 over a 12 year lifetime.

Recognizing the source of data for the accelerated wear rate due to underinflation, it might be expected that the condition would be overstated in the interest of marketing underinflation sensors. A much larger cost saving potential however, is indicated by Mr. Robert Brenner, Acting Chief Scientist NHTSA who in remarks to the Tenth Annual Goddard Symposium March 14, 1972, stated "Well known is the fact the underinflation causes excessive tire wear, possibly increasing tire costs by a third." If this assessment were used and the tire underinflation sensor achieved the impossible 100% effectiveness level then the average cost of approximately $60 per year per car (1.5 times at $40 each) could be reduced by $20 for a car lifetime saving of some $200. Because it is intuitively apparent that the cost savings can never approach one third of all tire costs, the savings of $14.40 per automobile lifetime is used for this study. There is an indication here though that a continuous reading onboard tire pressure sensing and display system might have the potential for achieving substantially larger savings. It is also probable, however, that such a sensing system would also cost substantially more thus the cost benefit picture would not necessarily improve.

The dollar value of tires lost because of failure has been difficult to estimate. Tire manufacturers are quite reluctant to discuss the frequency of warranty replacements for their products. An alternate source has been a DOT/NHTSA sponsored study on vehicle disablements, conducted in the San Francisco, California area in 1973. (Ref. 8.) The final report for that study estimates that about 6% of the vehicles in the study area suffer disablements, annually. In a sample of 1024 questionnaires, 172 (16.8%) indicated tire problems as the reason for displacement. Of this total, 41 (4.0%) were blowouts or tread separations. If these numbers are taken as typical, 0.24% (4% of 6%) of all cars will suffer a tire failure annually. In addition, some fraction of the other tire problems (generally flat tires) will also prove irrepairable. If 25% of the remaining tire problems are in this category, this would account for another 0.19% annually for a total of 0.43%. Then, over 12 years, 5.2% of all vehicles will suffer the premature replacement of a tire. If the mean age at which the loss occurs is halfway through the life of the tire,* the potential lifetime pay off is 2.6% of the value of a tire. At an average retail price of $40, this amounts to the princely sum of $1.04.

Something appears to be wrong. The 6% on-road failure rate implies a mean time between failures of 16 years, and a mean time between tire induced failures, of about 100 years! Subjectively, these figures look to be off by an order of magnitude. In the interest of offering a more plausible estimate, we shall assume that this is the case. The estimated lifetime cost of tire failures is then $10.40.

Brakes

Data on the amount of brake repair performed in 1975 is listed in Table 3-6. (Ref. 22.)** From these data, it is evident that wheel cylinder replacement is done 70% as often as lining replacement, and drums are refinished or replaced 78% as often as linings. On the disc brake side, we find caliper service and rotor work performed 33% and 90% as often as pad replacement, respectively. This high rate of refinishing for both drums and discs suggest that much of this work is done for reasons other than damage caused by shoes and backing plates. Since drum or disc replacements are performed only 10% as often as friction material replacement, a substantial fraction of this work may be due to damage.

If the automobile fleet is estimated at 110 million cars, 50% of which are equipped with front disc brakes, this yields 330 million drum brakes and 110 million disc brakes currently in service. This also yields an identical rate of replacement for friction material of 15% of all wheels per year or once every 6.5 years. Over a 12-year life, this means that each wheel is serviced 1.85 times for a total of 7.4 wheel refurbishments per vehicle.

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*Opinions differ as to whether this is a correct estimate. One author recalls reading that blown tires tend to be old, the other has heard that age does not matter. A third source (an enthusiast auto magazine) recommends thinning the tread depth to reduce the probability of failure when street tires are used in road racing events.

**This reference appears to omit do-it-yourselfers.

TABLE 3–6. BRAKE REPAIR DATA FOR U.S. IN 1975

(Source: Ref. 22)

Drum brakes		Disc brakes	
Shoes (wheels) Relined	38.3M	Pad sets (wheels)	16.9M
New	12.7M		
Total	51.0M		
Wheel cylinders Replaced	7.9M	Calipers Replaced	1.2M
Rebuilt	3.2M	Rebuilt	0.5M
Overhauled	24.4M	Overhauled	3.9M
Total	35.5M	Total	5.6M
Drums turned/ground	35.5M	Rotors resurfaced	13.0M
Replaced	4.5M	Replaced	2.2M
Total	40.0M	Total	15.2M

TABLE 3–7. SUMMARY OF POTENTIAL ECONOMIC IMPACTS

	Avg cost vehicle lifetime	Est % recoverable (max)	Max benefit
Tires			
Tread wear (inflation)	$12.00	100%	12.00
Fuel consumption (inflation)	$ 8.00	100%	8.00
Tire failure (all causes)	$10.40	50% inflation	5.20
Brakes			
Disc/drum refinishing	$29.00	50%	14.00
Disc/drum replacement	$30.00	70%	21.00

NHTSA supplied data indicates that the annual dollar value of drum refinishing operations is about $180 million, and drum brake lining replacement is worth $922 million. This yields an average cost of $5.27/drum, refinished and $18.07 per set of linings in conjunction with the previous data on number frequencies. Over a 12-year life, the cost of brake service is then

	Cost	Number	Total
Shoes/pads	$18.07	7.4	$134
Refinishing drums/discs	$ 5.07	5.7	29
Replace drums/discs	$50 (est.)	0.6	30

If we take 50% of the disc/drum refinishing cost and 70% of the disc/drum replacement cost as recoverable with a 100% effective countermeasure, a lifetime economic savings of as much as $35 is possible.

Summary

Table 3-7 is a summary of the lifetime economic impacts to be derived from the proper care of tires and brakes.

3.1.2 Cost Estimates

3.1.2.1 On-board Sensors

Estimating the life cycle cost of an on-board vehicle sensor can be a difficult exercise. The first step is estimating the OEM cost of the device, assuming that some parts of it are fabricated separately from the rest of the automobile. Given the OEM cost of the device, it is then necessary to determine the cost of integrating it into the vehicle and what costs will be assessed to cover the vehicle manufacturer's handling costs, profit, and so forth. This determines the incremental cost of providing the vehicle with the sensor. In addition, one must estimate the cost of maintaining the sensor for the life of the vehicle by replacing consumed, worn-out, or damaged components as required.

The amount of manufacturer's mark-up -- the fraction of the price paid by an automobile manufacturer for a component added to yield the consumer's cost for that same component when he buys the automobile or replacement part -- is very difficult to assess and probably impossible to predict with great accuracy. Aside from the difficulty of trying to estimate tangibles such as how many man-minutes of assembly time will be required to install a particular device for a wide diversity of automobile types, weight, sizes, etc., there are the intangible factors such as, does the automobile manufacturer want to include the device because he believes it will sell more automobiles or does he feel it is an unnecessary frill, and he should make as much profit as possible? Alternatively, he may want to use the option route to give himself evidence that the public does not want safety.

For purposes of this analysis, we have assumed that the general mark up for on-board sensing systems is 200%; that is 200% is added, yielding a selling price 3 times the OEM cost. Thus, the consumer would spend $6.00 more on the price of a new automobile for a sensor that cost the automobile manufacturer $2.00. This is considered a reasonable compromise between the "factor of 4" used by Mr. John Webster of Chrysler Motors (Ref. 23) and the "factor of 2" derived for structural parts in a NHTSA paper by Mr. Charles Westphal, Jr. (Ref. 24). Mr. Webster's estimate was based primarily on electronic engine controls which are in general more exacting; therefore, more costly to test, install, and adjust in the factory (and in the field under new car warrantee) than any on-board sensor should be. The NHTSA-derived factor of 2 is for structural members that are significantly simpler to install and support than on-board sensors.

There must be some judgment applied to each on-board sensor to bias it on the high or low side of this factor of 3, but it should be recognized that until someone does an in-depth analysis (much more detailed than can be conducted in this program) of all cost factors from component production, to installation, to spare-parts philosophy, to warrantee incurred costs, etc., etc., the cost-benefit analysis will provide a good judgment estimate in support of practicality determination nothing more.

Cost factors for replacement parts are even more difficult to estimate. There are known examples of a factor of 30 or more between the OEM price of some components and the sales price in the auto service center. It does not seem reasonable to attempt to generate a generalized "factor" for aftermarket components because of the apparently very wide diversity of costing considerations. When it is considered to be a significant factor, we have attempted to associate the part in question with a similar part for which cost estimates can be obtained.

Any on-board sensing system will contain a certain minimum number of components which establish a floor price below which any practical system cannot go. Thus, it is not reasonable to "invent" and estimate the cost for those monitoring systems that have very low potential for consumer cost savings. They are doomed to be non-cost beneficial and must be justified on some other basis if they are to be considered for use.

Any practical on-board sensor system will consist of sensors, wiring with connectors and a display. It is difficult to conceive of a sensor system that costs less than $1.70. Such a system might include a sensor at $0.50, 10 feet of wiring with at least 2 connectors, and a minimum display. The lifetime cost to the consumer for such a system using a factor of 3 OEM to consumer mark up and a 20% maintenance allowance is

Sensor (1)	$0.50	
Wiring (10 ft and 2 connectors)	0.20	
Display	1.00	
	1.70	OEM
	5.10	Consumer Cost
	$6.12	with 20% maintenance allowance

It would appear therefore, that cost-benefit analysis of on-board sensor systems that have a potential cost saving of less than $10 should not be conducted.

3.1.2.2 Alternative Countermeasures

The principal competitor to on-board sensors is periodic motor vehicle inspection (PMVI). An overall view of the costs of periodic inspection is provided in References 25 and 26, which develop the cost structure for diagnostic inspection (Safety, Emissions, and Fuel Economy) and safety inspection, respectively. A similar analysis is provided in Reference 13, but a breakdown to the individual inspection item level is not provided. Tables 3-8, 3-9, and 3-10 from (Ref. 26) present the direct, indirect and total costs of semi-annual inspection on a subsystem basis. Further breakdowns are developed, where appropriate, in Section 3.2.

Although this analysis is based on a (state-operated) lane/bay inspection system, the costs of inspection for an appointed garage are shown in Ref. 26 to be similar. The salient feature of this analysis is the myriad of costs that add themselves to the basic inspection labor, which is, by itself, a fairly small number. As a generalization on the desirability of on-board sensors (with on-board readouts) versus PMVI, it can be stated that on-board sensors offer real-time detection of vehicle faults, but do not force the owner to make repairs (as does PMVI). In cases where the costs of sensors are comparable to PMVI (which occur fairly regularly), the decision as to which approach is preferable must be based on the relative effectiveness of each of the two methods, which is not easy to determine.

TABLE 3–8. DIRECT COST APPORTIONMENT OF PERIODIC MOTOR VEHICLE INSPECTION

	Initial inspection			Reinspection				
Subsystem	Man min.	% of total	Annual cost	Rejection Rate	Man min./cert	% of total	Annual cost	Item Total
Tires and wheels	3.00	12	$0.99	13%	0.39	8	$0.12	$1.11
Steering	0.75	3	0.25	6%	0.05	1	0.02	0.27
Alignment	2.80	11	0.92	14.8%	0.41	9	0.13	1.05
Suspension	2.80	11	0.92	6.5%	0.18	4	0.06	0.98
Brakes	10.40	43	3.43	27.8%	2.89	62	0.92	4.35
Lights	1.00	4	0.33	35%	0.35	8	0.11	0.44
Electrical	1.00	4	0.33	23.7%	0.24	5	0.08	0.41
Glazing	0.20	1	0.07	2.3%	0.005	0.1	0.00	0.07
Body	0.40	2	0.13	2%	0.01	0.2	0.00	0.13
Fuel	1.00	4	0.33	6%	0.06	1	0.02	0.35
Exhaust	1.00	4	0.33	8%	0.08	2	0.03	0.36
Total	24.35	100	$8.04		4.66	100	$1.48	$9.52

Source: Ref. 26

TABLE 3–9. INDIRECT COST ALLOCATION OF PERIODIC MOTOR VEHICLE INSPECTION

	Assignable costs*			Non-assignable costs*	Total*
	Bldg.	Equip.	Owner time		
Tires and wheels	$ 0.04	---	$ 0.13	$ 0.78	$ 0.95
Steering	0.02	0.02	0.06	0.62	0.73
Alignment	0.09	0.49	0.15	0.83	1.56
Suspension	0.04	0.03	0.06	0.63	0.76
Brakes	0.31	0.46	0.26	1.15	2.18
Lights	0.03	0.01	0.35	1.33	1.72
Electrical	0.03	---	0.23	1.05	1.31
Glazing	0.01	---	0.02	0.52	0.55
Body	0.00	---	0.02	0.51	0.53
Fuel	0.02	0.02	0.06	0.62	0.72
Exhaust	0.02	0.03	0.08	0.66	0.79
Total	$ 0.61	$ 1.06	$ 1.40	$ 8.71	$ 11.78

*per vehicle-year
Source: Ref. 26

TABLE 3–10. TOTAL COST OF PERIODIC MOTOR VEHICLE INSPECTION

Vehicle subsystem	Direct* costs	Indirect* costs	Compliance* costs	Total* costs
Tires/wheels	$ 1.11	$ 0.95	$ 0.81	$ 2.87
Steering	0.27	0.73	1.66	2.66
Alignment	1.05	1.56	2.18	4.79
Suspension	0.98	0.76	2.72	4.46
Brakes	4.35	2.18	2.37	8.90
Lighting	0.44	1.72	1.22	3.38
Electrical	0.41	1.31	1.10	2.82
Glazing	0.07	0.55	0.10	0.72
Body	0.13	0.53	0.79	1.45
Fuel System	0.35	0.72	0.41	1.48
Exhaust System	0.36	0.79	0.41	1.56
Total	$ 9.52	$ 11.78	$ 13.77	$ 35.09

*Costs units are $/(Vehicle Year)
Source: Ref. 26

3.1.3 Effectiveness

The lifetime cost of accidents within each candidate area (Table 3-4) represents an upper limit on the safety impact of the corresponding on-board sensor, or other countermeasure. Similarly, the economic impacts summarized in Table 3-6 represent an upper limit on the economic benefit. The purpose of this section is to develop guidelines for evaluating the effectiveness of sensors or other countermeasures in recovering this benefit.

3.1.3.1 Effectiveness of On-board Sensors

The function of any sensor and its associated display is to communicate information to the driver. This information is then processed by the driver, whose function can be visualized as consisting of four sub-processes. (Ref. 27.)

1. Perception (sensing the information);
2. Comprehension (understanding or recognizing the information).
3. Decision (making a decision based on the information).
4. Action (performing some physical action based on the decision).

None of these sub-processes can be regarded as 100% reliable.

Some insight into how these processes function in the absence of sensors can be gleaned from the accident case re-evaluations performed in Task 2. In many instances, the post accident investigation revealed that the vehicle operator was aware of a deficiency in the vehicle prior to the accident. The extent of driver unawareness is tabulated in Table 3-11 for eight candidate sensor areas. It is interesting that in the two most safety critical areas, brakes, and tires, a substantial fraction of drivers appear willing to ignore known deficiencies. In the jargon of the information processing model described above, they make incorrect decisions based on information perceived and recognized.

The identification of candidate areas in Task 2 utilized the sum of indictments for unaware cases only. This is equivalent to assuming that an on-board sensor would have unit effectiveness on unaware drivers, and no effect on drivers already aware of the vehicle deficiency. If this assumption is used to re-define the upper bound on the sensor accident cost impact, the results are listed in Table 3-12.

It is probably unfair to assume that on-board sensors would have no impact on persons aware of performance deficiencies but not yet motivated to make the needed repairs, hence the numbers in Table 3-12 should not be

TABLE 3–11. UNAWARENESS OF VEHICLE DEFECTS INDIANA LEVEL C CASES, PHASES II-V

Sensor number	Description	Percentage unawareness based on cases	Percentage unawareness based on indictment
28	Brake performance	69	64
40	Tire pressure (underinflated)	100	100
37	Brake light intensity	100	100
42	Tire tread depth	54	51
10	Steering wheel play	80	83
39	Brake light electrical	100	100
21	Brake pad and lining wear	56	57
23	Brake fluid leak	72	58
4	Shock absorber	No data available	
41	Tire integrity	No data available	
12	Front end alignment	No data available	

TABLE 3–12. MAXIMUM LIFETIME ACCIDENT BENEFITS – ASSUMING SENSOR EFFECTIVE FOR UNAWARE DRIVER'S ONLY

Candidate area	Max accident benefit ($/vehicle)
Brake performance	79.75
Tire pressure	39.11
Brake light intensity	4.84
Tire tread	22.78
Steering wheel play	8.70
Brake light electrical	4.84
Pad and lining wear	25.28
Brake fluid leak	22.40
Shock absorber	9.27
Tire integrity	4.03
Front end alignment	2.02

construed as absolute upper bounds on sensor effectiveness. On the other hand, it is unlikely that any sensor will have 100% effectiveness on the unaware driver.* It must be recognized that motorists come in all shapes and sizes, some of whom will conscientiously seek to correct all faults brought to their attention, and some who will stubbornly resist all suggestions to take repair action until their vehicle ceases to operate. It is suggested that the unawareness levels indicated in the Indiana studies represent a level of sensor effectiveness beyond which it may be difficult to go.

Although the effectiveness of a sensor and display can be discussed qualitatively, it is difficult to estimate quantitatively.

There are two generic sources of information. The first is display systems for aircraft. Displays for these applications have developed a high degree of sophistication (and expense), utilizing such devices as flashing lights, audible alarms, and voice recorder messages to communicate warning messages as reliably as possible. However, air-crash investigations have repeatedly demonstrated that the message is not always comprehended. The problem in aircraft seems to be that enormous mental concentration is required to handle the normal flow of information, and that warning messages are occasionally screened out.

In automotive applications, similar problems can develop, albeit for different reasons. Many accidents occur because of driver inattention** which means that drivers fail to allocate a sufficient fraction of their mental facilities to the driving task. With regard to sensors, this poses a most critical problem when the warning requires immediate action, as when a brake partial failure occurs. The Indiana Level C data on this subject is very sparse: only two accidents have been attributed to partial failures. In one of these, the differential pressure switch (DPS) was working, but the warning was not observed. In the other, the DPS did not work. Although the problem in the first case may have been a failure of perception, the possibility of comprehension failure can not be dismissed.

In instances where the driver is unaware of the meaning of a display, he will have difficulty comprehending it and will tend to make incorrect decisions. A tentative indication of the current state of awareness of automotive displays is provided by a recent parking lot survey conducted in support of the Manual Brake Inspection Procedures program (DOT-HS-5-01188). Out of a sample of 31 drivers, (all workers at Avco) 13 (42%) did not know of the existence of the brake warning light or what it indicated. It is concluded that failures of comprehension could significantly reduce the impact of on-board vehicle sensors.

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*For example, if a brake light sensor reduces the mean time to repair a failed lamp from 4 months to two weeks, its effectiveness is not 100%, but 87%. (See Ref. 28.)

**13% certain plus 6% probable in Indiana Level C cases, Phases II-V.

Finally, there is the question of perception. Cockpit displays, with electrical warning lights or buzzers, are expected to be highly perceptable. However, buzzers are not necessarily comprehensible as to the nature of the fault indicated. Certain audible displays (brake squealers and tire whistlers) may not be perceptable to persons who have difficulty hearing high pitched sounds.

Overall, deficiencies in three of the four processes: perception, comprehension, and decision are expected to significantly impact the effectiveness of on-board vehicle sensors. Moreover, the relative effectiveness of competing sensor display concepts within the same area will have a significant impact on the preferred solution to a specific problem.

Although it is risky to generalize on the merits of various display concepts, Table 3-13 presents a list of comments on a variety of display features. No single display concept can be regarded as perfect, particularly when considerations of cost are included. The display must compromise between bellowing its message so forcefully that the driver will hear it - which may startle or annoy him - and being so unobstrusive that it escapes his attention.

3.1.3.2 Effectiveness of Alternative Countermeasures

The baseline for the accident cost calculation has been an assumption that the vehicle is not subject to periodic inspection. However, since a majority of states (33 as of this writing) currently have periodic motor vehicle inspection (PMVI) programs (of varying stringency) a more appropriate baseline for the accident cost calculation is the state of vehicle condition prevailing under a typical PMVI state.

The ultimate demonstration of inspection effectiveness would be that provided by reduced accidents. However, since the portion of accidents attributable to inspectable defects is small, the detection of this difference is quite difficult. A NHTSA sponsored study was recently performed to determine the feasibility of demonstrating inspection effectiveness through accident reduction. (Ref. 29.) Although it is concluded that a demonstration of an accident rate reduction due to PMVI is possible, existing studies of the relationship between PVMI and accidents are inconclusive. In fact, some comparisons show a negative relationship between PMVI and accidents. Although it is currently not possible to demonstrate the effectiveness of PMVI through accident reduction, studies are currently in progress to determine the effectiveness of inspection in improving vehicle condition. Unfortunately, results of these studies are not yet available. A preliminary attempt was made to estimate the effectiveness of inspection in Reference 26. However, these effectiveness results are of questionable validity, and were described in the text as "lying in the correct range - between zero and one." At least they

TABLE 3–13. COMPARISON OF DISPLAY FEATURES

Display feature	Perceptability (Ability to get the driver's attention)	Comprehendability (Ability to tell him something)	Comments
Visual in cockpit	good	depends on labeling	
Flashing light	excellent	depends on labeling	may be annoying
Display when affected system exercised	poor to good (depends on subsystem) brakes? stop lights - poor	good	
Latch to "on" condition whenever fault occurs	good to excellent	fair to good (depends on labeling)	
Audible (in cockpit)	excellent	poor	Detroit does not like, may be annoying
Audible (outside car)	poor to good	fair depends on subsystem	
Visual (outside car)	fair	depends on system	

are in agreement with Reference 13 which places the effectiveness of inspection between 45% and 75% (on the basis of questionable data). For lack of anything better, the data are reproduced in Figure 3-8. It must be observed that these estimates are derived from Government-operated inspection systems, which generally performed a maximum inspection* using state-of-the-art equipment. Whether these effectiveness estimates are applicable to PMVI as typically practiced by appointed garages is unknown.

3.1.3.3 Presentation of Results

There are three ingredients to the tradeoff between sensor techniques and/or alternative problem solutions:

1. The maximum lifetime benefit, based on accident prevention plus economic considerations.

2. The cost of the sensor concept.

3. The sensor/display effectiveness.

Although all three of these are difficult to quantify, the sensor/display effectiveness is probably the most difficult. For this reason, many of the results will be presented in parametric form, in which the sensor/display effectiveness is a free variable.

The techniques to be used are illustrated in Figures 3-9 and 3-10. The figure of merit for any sensor or alternative policy is its expected cost, computed over the vehicle lifetime. For the situation in which no action is taken, the expected lifetime cost is equal to the cost of accidents plus whatever other available economic costs may be incurred throughout the vehicle lifetime. This cost is represented in Figure 3-9 by the horizontal line labeled "no sensor". If a sensor (or other countermeasure) is applied to combat the problem, but has no effectiveness whatsoever, the lifetime cost is equal to the former cost plus the cost of the sensor. This is indicated as the y-axis intercept labeled A in Figure 3-9. If, on the other hand, the sensor is 100% effective in eliminating the problem, the lifetime cost to the vehicle owner is only the cost of the sensor, as indicated by point C in Figure 3-9. Finally, if the sensor has an effectiveness between 0 and 100%, the lifetime cost will vary along the line between points A and C.

Point B in the figure defines the break-even point, at which the lifetime costs with the sensor are equal to those without the sensor. If the sensor effectiveness is less than the corresponding abscissa value, the sensor is not cost beneficial. Conversely, above this "break-even" effectiveness point, the sensor is increasingly cost-beneficial.

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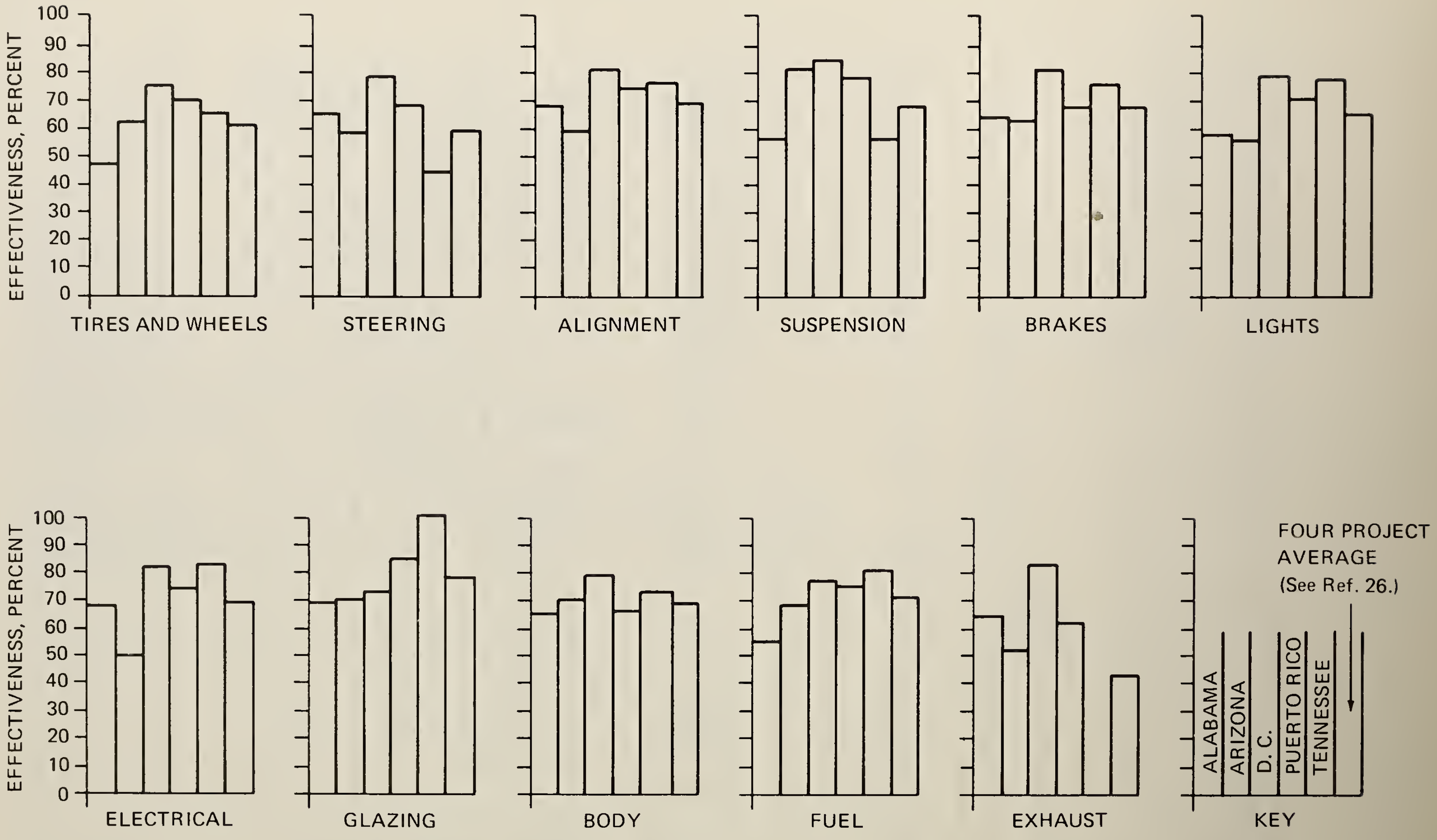
*For example, the brake inspection consisted of removal of two wheels, plus a dynamic performance test.



SOURCE: REF. 26

*REJECTION RATE MORE THAN DOUBLED FROM P1 TO P2. SIMPLIFIED FORMULA YIELDED NEGATIVE MEASURE OF EFFECTIVENESS.

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Figure 3–8 EFFECTIVENESS OF PROJECT INSPECTIONS USING SIMPLIFIED FORMULA

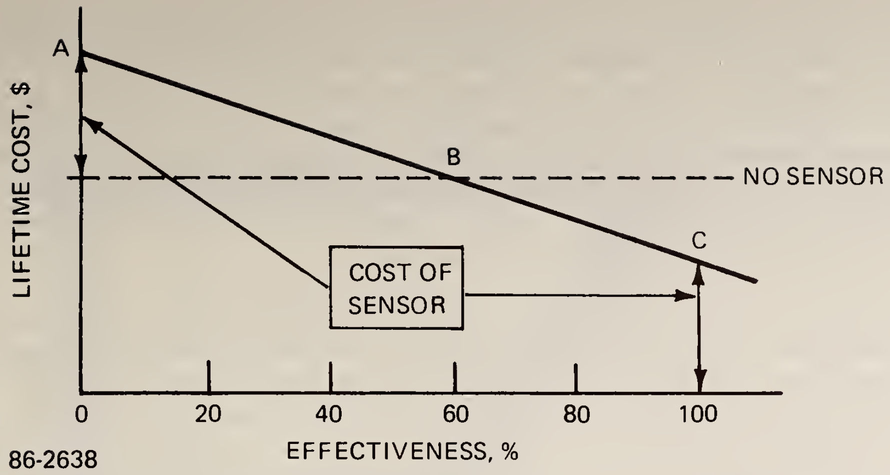

Figure 3–9 PARAMETRIC EVALUATION OF SENSOR CONCEPTS

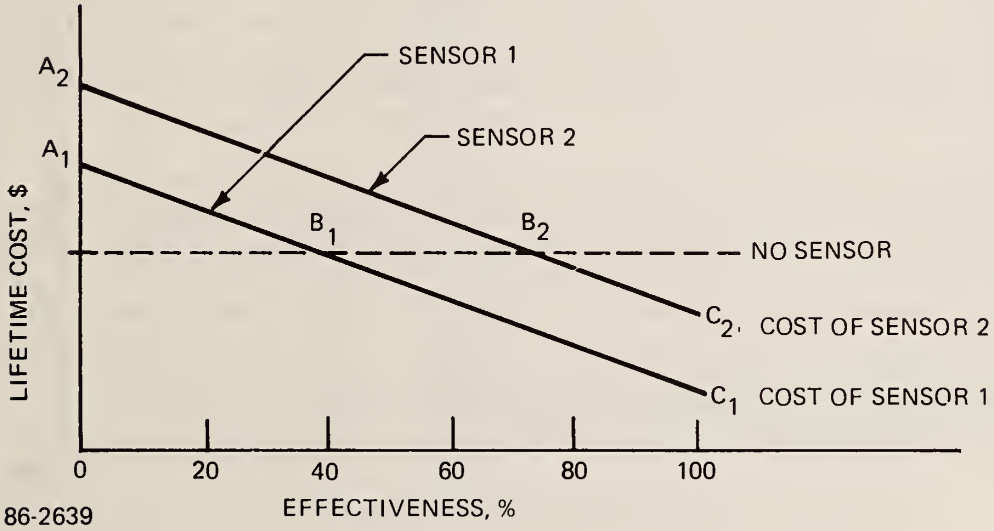

Figure 3–10 EVALUATION OF ALTERNATIVE CONCEPTS

Two or more concepts can also be evaluated on a single graph as shown in Figure 3-10. Each sensor appears as a straight line, parallel to that for all other sensors. From this figure we can see that Sensor 2, which has a higher cost than Sensor 1, also has a higher break-even effectiveness. Since the lines are parallel, Figure 3-10 also shows that for Sensor 2 to have a lifetime cost equal to that of Sensor 1, its effectiveness must exceed that of Sensor 1 by a fixed quantity equal to the difference in the break-even effectivenesses.

Obviously, whenever Sensors 1 and 2 have equal effectiveness, the cheaper sensor is preferred. In order to simplify the comparison when the effectivenesses are not equal, it is useful to recast the important information as shown in Figure 3-11. Here the abscissa and ordinate values correspond to the effectiveness of Sensors 1 and 2, respectively. The breakeven effectiveness of Sensor 1 demarks a vertical line to the left of which Sensor 1 should not be used. The breakeven effectiveness of Sensor 2 demarks a horizontal line below which Sensor 2 should not be used. Finally, the relationship for equivalence between sensors defines a 45 degree line that divides the remaining space between Sensors 1 and 2. Thus, over the entire range of possible effectiveness values (0-100%) for each sensor, the figure indicates that preferred approach to the particular problem being analyzed. When both sensors are ineffective neither should be used. When both sensors have high or nearly equal effectiveness, Sensor 1 should be used. When Sensor 2 has high effectiveness (and Sensor 1 does not) it is preferred.

An additional piece of information that may be placed on a graph of either (Figure 3-9 and 3-11) type is the implied limit on sensor effectiveness represented by the percentage unawareness data shown in Table 3-11. For example, if only 65% of all drivers are unaware of a particular problem in the absence of a sensor, it is possible that a sensor would have little impact on the 35% who are aware. If this is true, the sensor effectiveness is bounded above by 65%. This can be indicated by a vertical or horizontal line at the appropriate level of effectiveness.

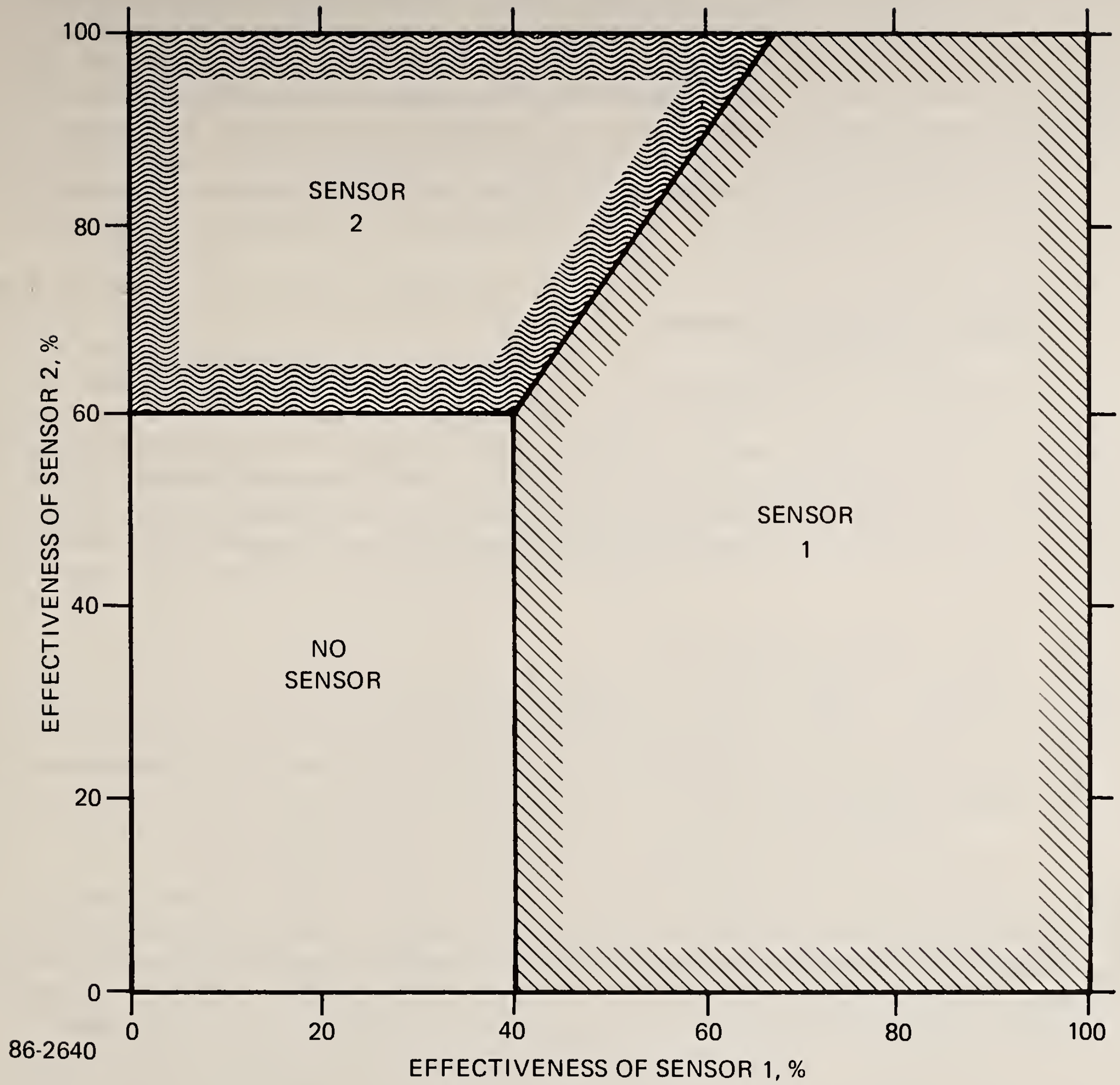

Figure 3–11 SIMPLIFIED METHOD FOR DETERMINING THE PREFERRED SENSOR

3.2 APPLICATION OF METHODOLOGY - SPECIFIC SENSOR CONCEPTS

For each of the candidate areas, the sensor identification process has involved five steps. First, the justification for the measurement area has been reviewed. This review had led to a determination of the functional requirements for the sensor. Third, a list of candidate sensing techniques has been developed for each measurement area. These candidate techniques have then been subjected to tradeoff analysis to determine the best method of performing the indicated function. This analysis has included a preliminary cost-benefit analysis of each concept. Finally, the results of the evaluation for each measurement have been summarized and recommendations have been made.

3.2.1 Brake Performance Sensor

3.2.1.1 Review of Justification

This measurement area achieved the highest ranking of all those considered in Task 2, principally because the condition of "brake performance" has been defined in the broadest possible sense. If one wishes to be precise, it is possible to subdivide brake performance faults into such categories as:

1. Side-to-side imbalance.
2. Improper proportioning (front-to-rear).
3. Incorrect gain (too much or too little retardation per unit of pedal force).
4. Total/partial failure (a limiting case of zero gain).

This was not done in this study, for two reasons. First, the accident investigation literature tends to use the phrase brake imbalance or brake performance in a broad sense. This is done because the categorization of brake performance faults in the real world is not as clear cut as it is in the abstract. Cases have been studied in which grease contamination, brake fluid leaks, and metal-to-metal contact between friction surfaces have all been present, and these defects variously distributed over several wheels. During the course of the accident, the vehicle may have suffered both directional control problems and total braking effort difficulties, compounded by driver errors such as improper steering and locked wheel braking, as well as other vehicle problems such as improperly inflated tires and defective shock absorbers. In such situations, it is difficult to pin a precise label on the nature of the defect.

There is, however, a second reason for using a broad definition of the term brake imbalance. This relates to the capability of the sensor.

Just as brake performance faults do not lend themselves to easy categorization, neither do brake performance sensors. For example, it is possible to conceive of a sensor that will detect side-to-side imbalance as well as defects in front-rear proportioning. It is difficult to state which of these functions is primary and which is secondary.

With this background, it was decided to adopt a broad definition of the term brake performance for purposes of Task 2, and to sort out the difficulties later. The brake performance sensor, as identified in Task 2, is a device that would indicate improper stopping force at any wheel or wheels for any cause.

The Indiana Level C data identifies a total of 31 cases involving brake factors. (Table 2-3.) Eight of these involved total hydraulic failure on pre-1968 cars and were not reviewed. Of the remaining 23, two involved design deficiencies, rather than in-use defects. Sensor application was not considered relevant in these cases. Two additional cases did not identify the failure mode with sufficient precision to determine whether a sensor was applicable. In the remaining 19 cases, application of a brake performance sensor was cited as potentially relevant. Application of the standard Task 2 screening procedures for strength of indictment and awareness produced the weighted total of 6.84 cases for this sensor.

Obviously, citation of the sensor as potentially relevant in every case involving an in-use brake defect provides an upper bound estimate of its applicability. This is consistent with procedures applied on other sensor concepts, and also with the objectives of Task 2 (candidate areas). At this point, however, it is appropriate to re-evaluate the potential impact of a brake performance sensor on a more critical basis.

In all but one of the 19 cases in which the brake performance sensor was judged applicable, other (more specialized) sensors were also judged applicable. The extent of the overlap between brake system faults is indicated in Table 3-14. Obviously, the case for a brake performance sensor rests on its ability to detect a variety of system-level faults in the brake system.

Questions have been raised as to whether it is plausible to expect an on-board performance sensor to detect worn linings, in view of the Bendix findings (Refs. 9 and 10), on this same subject. (See also Section 3.2.7, Lining Wear.) The answer is that a performance sensor probably will not detect thin linings, but may detect the consequence of metal-to-metal contact between linings and drums. From the standpoint of effectiveness, it is preferable to detect incipient failures (thin linings) rather than actual failures (metal-to-metal contact). The advantages of early detection include an increased lead time in which to

TABLE 3–14. OVERLAP BETWEEN BRAKE FAULTS IN INDIANA LEVEL C CASES JUDGED AMENABLE TO PERFORMANCE SENSING

One Fault

1 - Partial hydraulic failure (performance fault)

Total: 1 case

Two Faults

6 - Wear + performance
1 - Fluid leak + performance
1 - Grease leak + performance
1 - Stuck cylinder + performance

Total: 9 cases

Three Faults

2 - Wear + pedal overtravel + performance
1 - Adjuster + overtemp + performance
1 - Fluid leak + pedal overtravel + performance

Total: 4 cases

Four Faults

1 - Low reservoir + fluid leak + grease leak + performance
1 - Fluid leak + grease leak + pedal overtravel + performance

Total: 2 cases

Five Faults

1 - Wear + fluid leak + adjuster + pedal overtravel + performance
1 - Fluid leak + grease leak + adjuster + pedal overtravel + performance
1 - Reservoir level + fluid leak + grease leak + pedal overtravel + performance

Total: 3 cases

make the repair, reduced exposure to operating a hazardous vehicle, and potential cost savings in reduced drum/rotor refinishing. This does not imply, however, that a late warning is useless. Many other sensor concepts examined in this study provide a warning only after the item monitored has reached an unsafe level. If lining wear is not significant from a performance standpoint, then its non-detection does not matter. Conversely, if it is significant, then it may be detected by a performance sensor. Finally, it should be noted that total exclusion of wear-related cases from consideration still permits a brake performance sensor to qualify for further investigation.

A more interesting question concerning the justification for a performance sensor is whether the concept can be justified for current production automobiles, on which the use of single-piston (floating or sliding caliper) front disc brakes is almost universal. Only two of the 31 Indiana Level C brake cases involved cars equipped with disc brakes. Neither of these was single piston systems. It cannot be stated that disc brake vehicles were infrequently indicted in the Indiana study because they were (or are) more reliable, although they may well be. Rather, they were simply rare in the study population.

In summary, the case for a brake imbalance sensor rests on its ability to detect system-level faults in the brake system. Among these is the somewhat controversial condition of lining wear. However, even if this condition were eliminated from consideration, the performance sensor area retains a high ranking.

3.2.1.2 Functional Requirements

In Task 2, a brake performance sensor was defined as a device capable of detecting abnormal brake performance at any wheel or wheels. Obviously, this definition requires refinement before the details of an operating sensor can be worked out. In contrast to other defects such as low tire pressure and steering wheel play, which were quantified in the post accident reports, the Indiana data does not provide a quantitative measure of the brake performance faults. The problem is compounded by a stronger than normal tendency for the consequences of a fault to be both scenario and vehicle design dependent.

If one front brake (in theory either a front or a rear brake) suffers from a marked decrease in brake force, from whatever cause, there are four types of consequences:

1. A loss in total braking force, hence in available deceleration.
2. A yaw-torque; numerically the total imbalance multiplied by half the tread-width.

3. A disturbance in the front-to-rear proportioning and hence an increased likelihood of lock-up as the driver increases pedal load to achieve the deceleration expected and required.

4. A steering torque, caused by geometrical factors in conjunction with the brake force imbalance.

If the imbalance is caused by one front brake developing more brake force than usual, rather than less, Items 2 and 4 remain; Item 3 is modified because the front-to-rear ratio is disturbed and premature lock-up of the affected wheel is likely, but the driver should not have to increase pedal load to achieve the deceleration he originally sought; Item 1 no longer exists.

If the loss of brake force is in one rear wheel, Consequences 1, 2 and 3 exist, but to a decreased degree. This is because the rear brake forces are, as a rule, less than half front brake forces at any given pedal force; and because vehicle directional stability is enormously improved if one rear wheel remains unlocked, rather than both locking up. (In one sense, then, a rear imbalance can actually help.) If the rear imbalance is caused by an increase in brake force, 2) and 3) remain true together with a possible increase in the likelihood of a lock-up at the back.

Relative to Consequences 1 and 3, there is no clear-cut threshold as to how much loss of braking is critical. Figure 3-12 (Ref. 30) illustrates this point. It can be seen that the lower threshold of stopping distance reduction for which accident prevention or severity reduction can currently be postulated is about 10%. These calculations are based on a small sample of skidding accidents. Additional investigation can be expected to further refine this figure.

Similarly, there is no clear-cut threshold on the degree of degradation required to transform an unlocked wheel, maximum effort stop into an uncontrolled skid. This depends on vehicle design, accident scenario, and driver capabilities. Although locked wheel braking is seldom observed in controlled studies of driver performance, (Ref. 10), it is all too evident in the Indiana Study (Table 3-15). Whether this discrepancy in subject performance between laboratory and the real world relates to the psychological conditions of the experiment (probably), or to the specific choice of vehicles used in the experiment (unlikely), cannot be definitively established.

Although the consequences of brake defects on the lateral dynamics of the vehicle can be described qualitatively, the definition of quantitative standards is perhaps even more difficult than it is for axial deceleration.

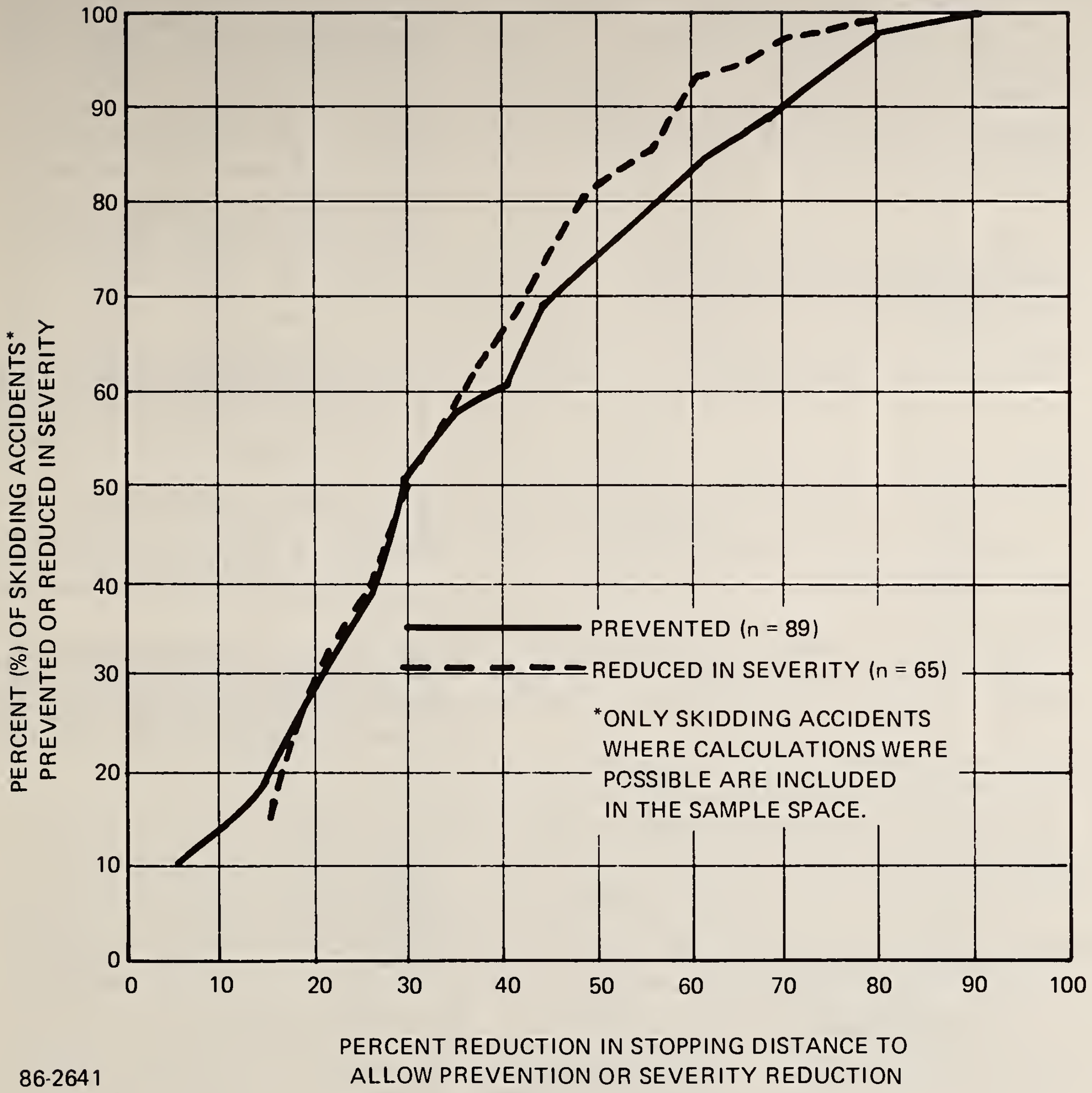

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Figure 3–12 CUMULATIVE RELATIVE FREQUENCY DISTRIBUTION OF RECENT REDUCTION IN STOPPING DISTANCE TO ALLOW ACCIDENT PREVENTION OR SEVERITY REDUCTION

TABLE 3–15. SUMMARY DRIVER ACTIONS, BRAKE PERFORMANCE AND VEHICLE DYNAMICS – INDIANA LEVEL C CASES

Case No.	Locked wheels (skid marks)	Vehicle dynamics	Accident scenario*
546-082	Fronts only	Slid straight into U-2	Driver's inattention Causal-Certain LR brake contam. S/I prob.
652-113	All 4	Slid straight	IRPS gave Causal possibility to brake imbalance because Clayton brake inspection using tester results showed 50/350 on rears. Very unlikely that the brakes were involved because the driver steered to the left and the skid marks were virtually straight and superimposed.
710-131	Not known	Straight-on on RH bend then flying - VW	Driver apparently made almost no attempt to steer back into correct path. Braked instead.
730-186	None		Veered left on braking and struck oncomer.
758-144	All 4	Swerve to right and clockwise rotation	Slight unbalance on right rear and swerve to right resulted in premature right rear lockup which helped the rotation (over stress).
997-214	First both rears Then RF Then LF		
1018-222	RR & LF	Slid into rear end	Most of IRPS' indictment of the vehicle was the bald tires (with which one can't argue) and only a little the seized primary pistons on the left rear which would have reduced brake effort somewhat.
1027-225	Both rears	Spun right	"Hit" brakes - older driver
1030-227	None	Spun left into on-coming traffic	NC vehicle ahead braked heavily to avoid dog. Marks are cornering scuff - not locked up.
2197-045	All 4	Spun left	Hard braking for stop sign.
79-079	First RR, then LR, then LF	Anticlockwise spin	Agree with IRPS that poor (or inappropriate proportioning largely to blame.
2420-098	Rears only	Straight ahead	Rear ender - U-1's brakes very long pedal - RF-/rear tires over-inflated (37/26, 32/26. RF lower ball joint loose. Single system brakes (1960 car). Causal certain driver inattentive. Causal Possibility - brake operation and lockup might have been delayed due to brake condition.
2447-106	Both fronts (RF 34', LF 22')	Swerve left 12°, 5 ft.	Delayed recognition.
2477-112	Both fronts	Straight ahead	Delayed recognition.
2546-122	Right front	Spun	Icy road - attempted braking by pumping.
2567-127	Rears	All over the road	Began skidding on gravel. Excessive speed and improper correction cited.
2604-136	Both fronts (RF 60' later than LF)	Drifted left	Attempted to apply brakes while cresting hill at high speed.
2705-154	All four locked then unlocked to impact	Straight ahead	Attempted heavy braking.
3128-197	Right front	Vehicle pulled strongly right as driver braked heavily (low speed) and steered right.	Attempted swerve to avoid perceived obstacle. Rainy.
3141-200	None	Straight ahead	Non-emergency situation.
3668-263	All 4 - (some longer than others)	Straight ahead	Delayed recognition. Heavy braking attempted.

Abbreviations:
NC = non-contact (vehicle)
IRPS = Institute for Research in Public Safety
S/I = severity increasing
U-1,2 = Unit 1, 2

Number/Number = $\frac{\text{inflation actual}}{\text{inflation spec.}}$

or

$\frac{\text{brake effort (R)}}{\text{brake effort (L)}}$

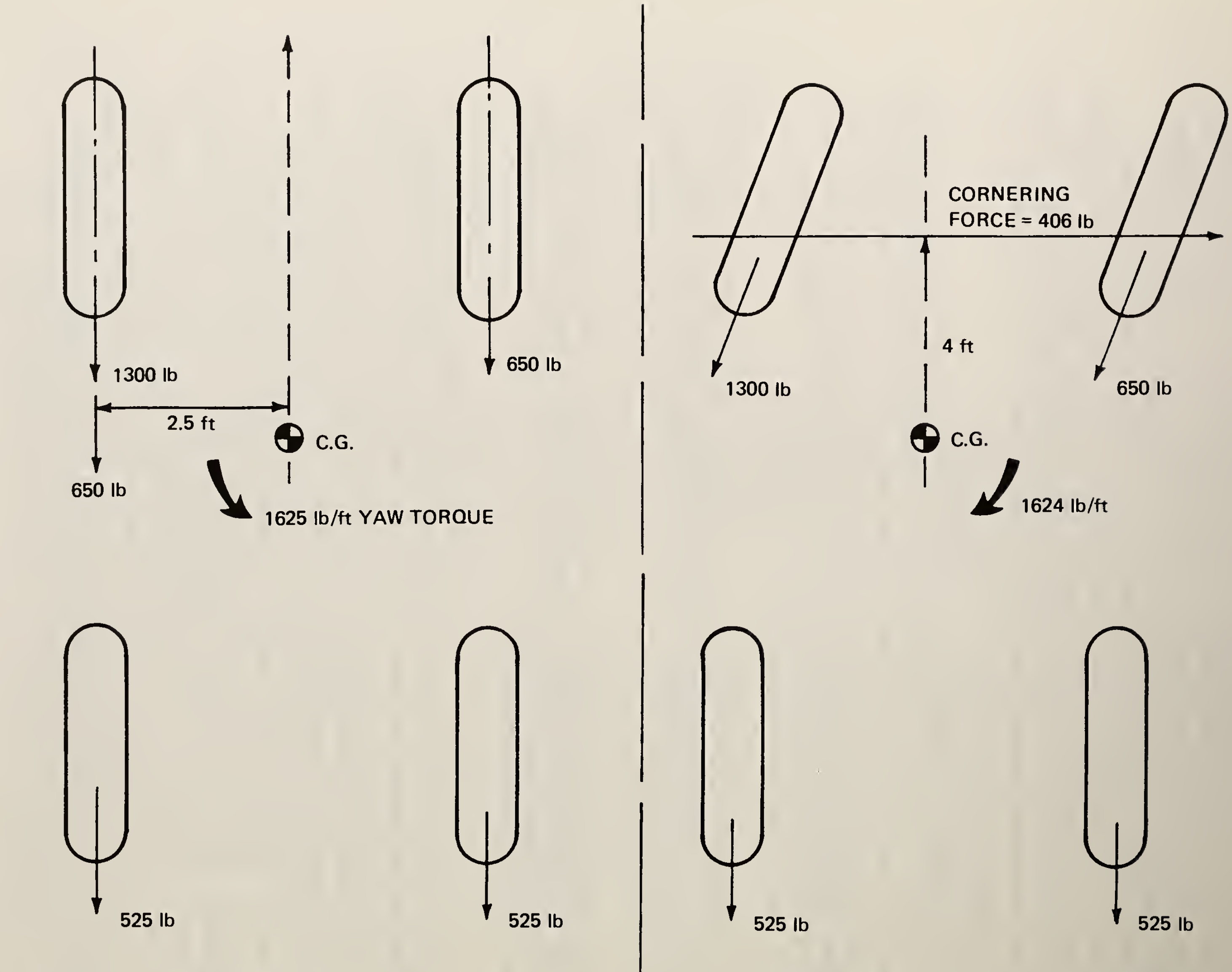
Most domestic car brakes provide front-to-rear effort ratios of about 70/30 at the higher pedal loads. This means that each front brake is providing about 35% of the total braking force. On a 5000 lb. loaded car, during a 0.75 g stop, this represents a braking force of about 1300 lbs. The loss of all this force is unlikely - maybe even impossible -- but even half of it would result in a reduction in available deceleration from 0.7 g to 0.57 g, or 19%. It also represents a yaw torque of 1625 lb-ft. (Figure 3-13.) This could undoubtedly be counteracted by a careful driver steering in such a way as to generate an opposing, equal cornering force.

The two diagrams in Figure 3-13 show a simplified version of the forces and torques, plus an approximation of a correcting torque from a steering input. Obviously, the steer angles confuse the issue, because the brake imbalance is no longer over an axis parallel to that of the car and, the cornering force is not along a line perpendicular to the car's axis, but instead is along a line between the left and right front wheels' axes. The principle, however, remains.

The requirement for the driver, in a situation which may be close to an emergency, to make a carefully balanced steering correction, while trying to modulate his braking effort, is formidable and may well be beyond many drivers.

Finally, there is the effect that the brake force imbalance is likely to have on the steering wheel. Figure 3-14 shows views from in front of the car of a steerable front wheel, (a) and (c), and the plan views of the contact patch (b) and (d).

It can easily be seen that the existence of a brake force results in a steering torque about the steering axis. This is normally balanced by an equal and opposite input from the other front wheel. If, however, there is a net brake imbalance, then there will be a net input to the steering linkage. A commonplace figure for camber offset might be about 2 inches. An imbalance force of 650 lb. would result in a torque input of 1300 lb-in. The steering ratio is generally about 20:1 and the reverse steering efficiency is probably about 40%, so this imbalance reaches the driver with a steering wheel torque of 26 lb-in or a rim force of 3.25 lb or so. (See Table 3-16.) This is not an enormous amount and certainly not one which the driver cannot counter. But he may be contending into some kind of emergency, his normal steering input forces are less than 3 lb. (except for a violent maneuver) and he has to deal with this on top of other demands on his attention and skill. Moreover, in circumstances where a steering pull comes as a complete surprise, even the most skilled drivers may not have time to react.



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A. UNCOMPENSATED YAW TORQUE

B. YAW TORQUE CORRECTED BY STEERING INPUT

Figure 3–13 DEVELOPMENT OF VEHICLE YAW TORQUE DUE TO YAW BRAKE IMBALANCE

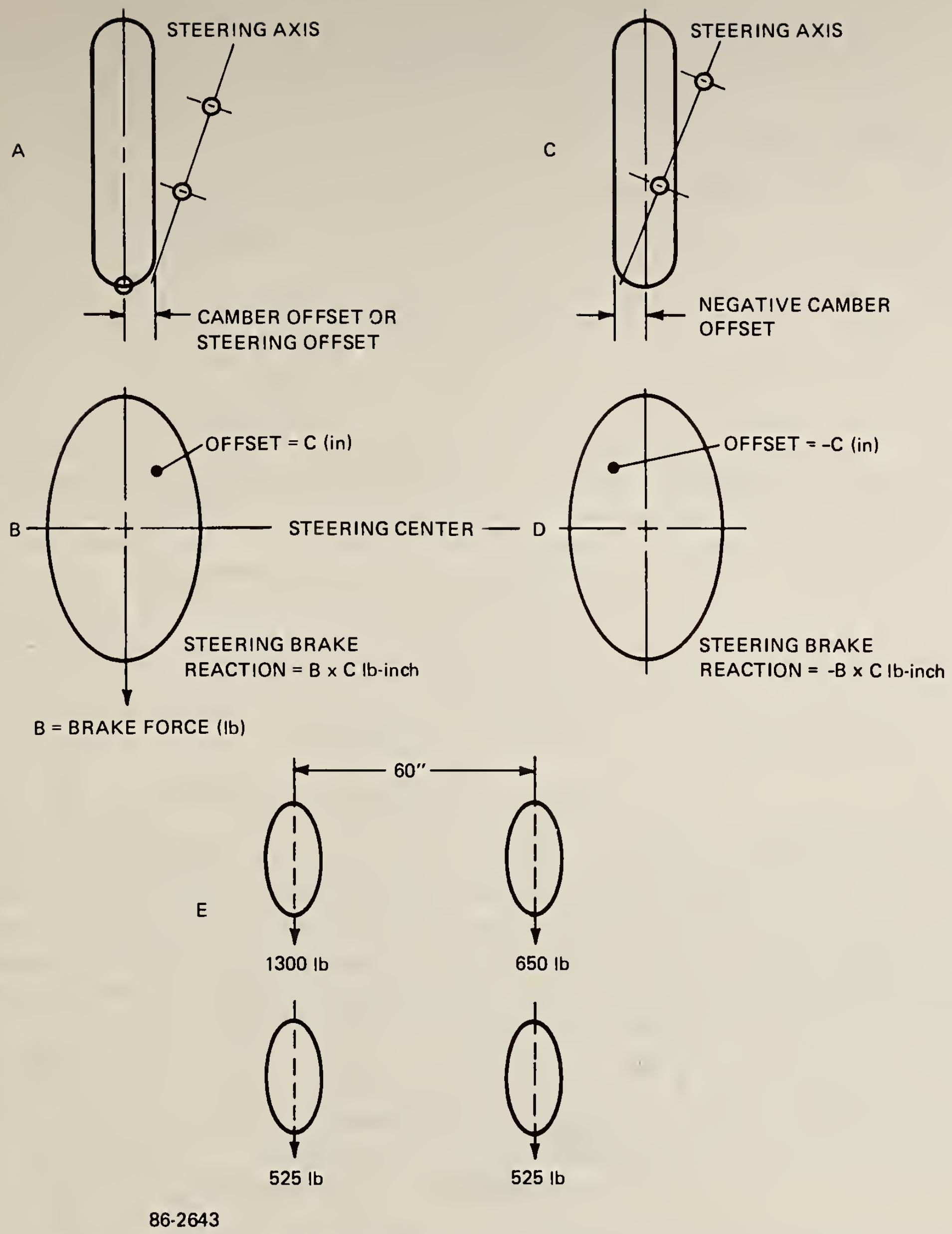

Figure 3–14 DEVELOPMENT OF STEERING TORQUE DUE TO BRAKE IMBALANCE

TABLE 3–16. SAMPLE CALCULATION OF VEHICLE AND STEERING TORQUES
(See Figure 3–14e)

Yaw Torque = 650 x 30 = 19500 lb-in
= 1625 lb-ft.

If Camber Offset = 2 inch.

Brake Steer (left side) = 1300 lbs x 2 in
= 2600 lb-in

(right side) = 650 lbs x 2 in
= 1300 lb-in

Net (L - R) = 1300 lb-in

If the steering ratio is 20:1 and reverse efficiency is 40%, pull at steering wheel =

$$\frac{1300}{20} \times .40$$

= 26 lb-in

If steering wheel rim diameter = 16 inches

$$\text{rim force} = \frac{26}{16} \times 2 = 3.25 \text{ lb}$$

Some cars, notably front wheel drive models, are designed with either zero or even negative camber offset. These latter are intended to provide some compensation for unbalanced brakes or drive thrust forces in that the imbalance tends to steer the wheels in such a direction as to counter the yaw torque. Among cars so designed are:

Zero camber offset	Cadillac Eldorado Oldsmobile Toronado Saab 99 Mercedes Benz 450 SE & SEL
Negative offset	VW Rabbit or Scirocco VW Dasher

Most new Ford cars from Europe (for example, the Fiesta) will be set up with zero or negative offsets. It also seems probable that many rear wheel drive cars will go to zero or very small offsets, because this offers other advantages, such as reduced tendencies to wheel imbalance shake.

Before concluding this discussion of lateral dynamics, some results from "the literature" should be cited.

It seems to be generally recognized that side-to-side imbalance in the rear wheels does not produce significant vehicle controllability problems. Bendix (Ref. 10) found that total loss of one rear brake was not even detected in a majority of cases. On the other hand, both the Bendix report and the Clayton SAE paper (Ref. 31) indicate that a very serious handling problem is created by front wheel imbalance. The Bendix report recommended that brake imbalance limits not be established on the basis of vehicle handling criteria. This seems to be totally inconsistent with the results of their study which showed that 75% of all drivers failed to keep a compact vehicle with manual steering within a standard 12 foot lane when the road surface is dry and the front wheel imbalance was 100%. Their test results seem to say that nearly all compact vehicles driven on a dry road will experience a severe controllability problem with 100% left-to-right front wheel imbalance, and that a substantial percentage of full-sized automobiles will experience the same difficulty. The Clayton paper indicated a much lower tolerance to front wheel imbalance - 30% at a force level (strongest brake) of 50 lbs or above is considered hazardous. The inconsistency in conclusions between these two reports is too large to accept. Since brake faults causing imbalance have been identified by the Indiana accident study as the most significant vehicle cause for accidents, it would be most advisable that another study be undertaken to resolve this inconsistency and establish performance standards.

In addition to the problems previously discussed, (vehicle dependence, scenario dependence, differences of opinion in the literature) a further complication is posed by a variety of possible definitions for brake imbalance. However, the concepts involved are quite simple. If all possible combinations of right side (R) and left side (L) brake force are associated with the points in the first quadrant of a cartesian coordinate system, the ideal condition of equal right and left side brake forces corresponds to a 45° line through the origin. (Figure 3-15.) Fixed differences between L and R (absolute imbalance) correspond to lines parallel to the ideal line, on either side. Fixed ratios (percentage imbalance) correspond to lines of varying slope, each passing through the origin. A complicating factor is the variety of specific choices possible to define percent imbalance.

If the brake forces developed at the opposite ends of an axle are A and B, then percent imbalance could be calculated in five different ways as:

$$\text{(i)} \qquad \frac{A - B}{A + B} \left(\frac{500 - 250}{500 + 250} = 0.33 = 33\% \right)$$

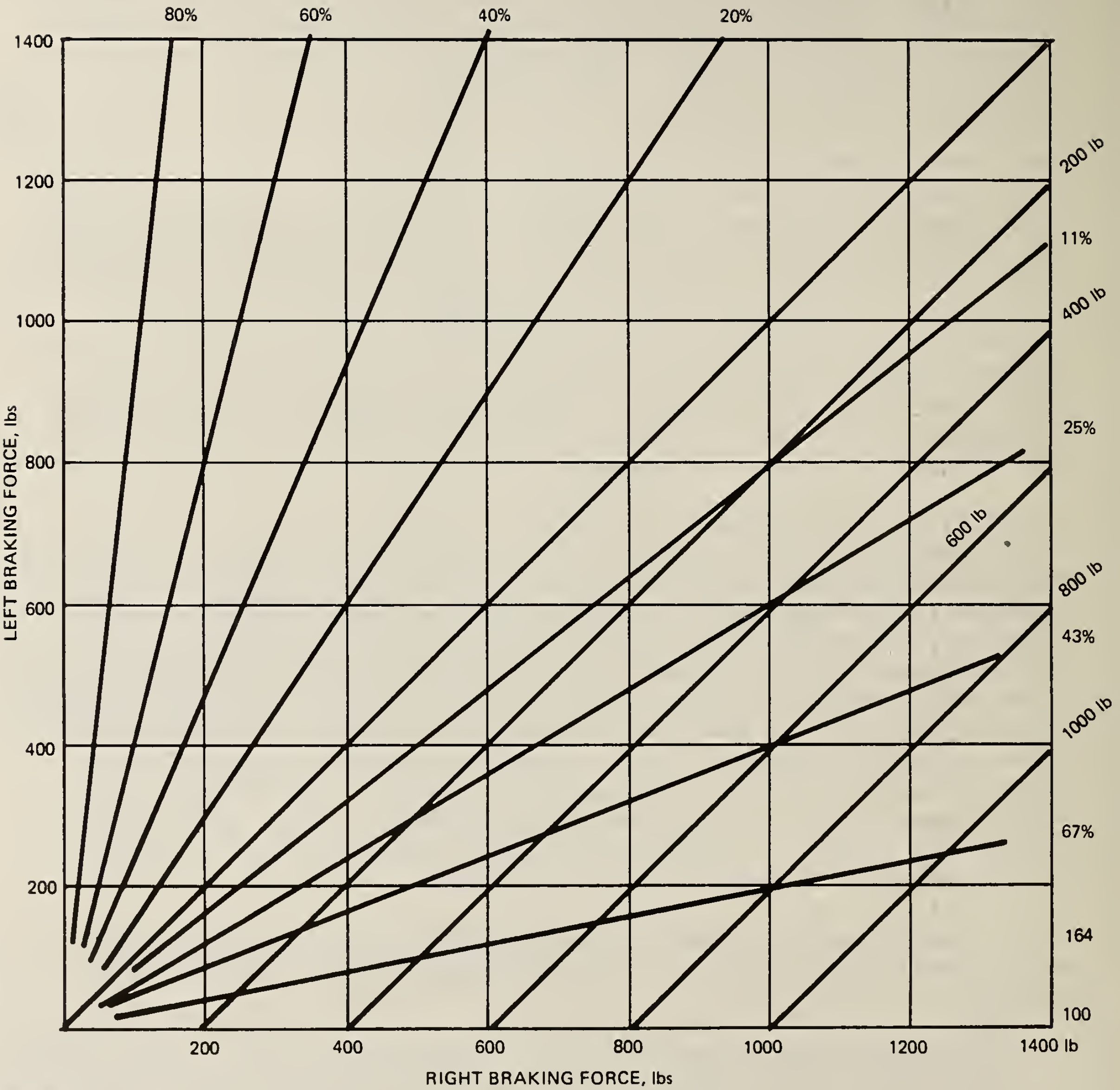

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Figure 3–15 FIXED VS PERCENT IMBALANCE

(ii) $$\frac{A - B}{A} \left(\frac{500 - 250}{500} = 0.50 = 50\% \right)$$

(iii) $$\frac{A - B}{B} \left(\frac{500 - 250}{250} = 1.00 = 100\% \right)$$

(iv) $$\frac{A - B}{2A} \left(\frac{500 - 250}{2 \times 500} = 0.25 = 25\% \right)$$

(v) $$\frac{A - B}{2B} \left(\frac{500 - 250}{2 \times 250} = 0.50 = 50\% \right)$$

The brief calculation which follows in each case displays the quantitative results where the two brake forces are 500 lb and 250 lb.

For purposes of this report, the first formula will be used.

Clayton (Ref. 31) uses a variation of formulas (ii) and (iii) in which the larger brake force appears in the demonstration; Bendix (Ref. 10) uses formula (i); and the NHTSA Vehicle-in-Use Inspection Standards (VIU) use different variations of formulas (ii) and (iii). The latter standard is ambiguous, it requires that $0.75 \leq A/B \leq 1.25$ or $0.75 \leq B/A \leq 1.25$, depending on which wheel is "the brake" and which wheel is "the brake on the other...wheel". If $A/B = 0.75$ (which passes) $B/A = 1.33$ (which fails), so the choice may be critical to the outcome of the test. If the standard is interpreted as being applicable both ways (to A/B as well as B/A) the numerical requirement is equivalent to ±11% on the reference formula. Bendix recommends a standard of ±20%, and Clayton a combination of absolute and relative standards, the latter corresponding to 25 to 30% on their own scale, and 14 to 18% on the scale of this report. (See Figure 3-16.) In summary, the standards proposed by the sources considered differ by nearly a factor of two, with the DOT standard the most stringent.

Next, there is the question of the level of effort at which the standard is applied. VIU imposes no constraint; Bendix has developed (for NHTSA) a low speed, high effort test machine; and Clayton offers both high speed, low effort, and low speed, high effort equipment. It can only be said that technical opinion is far from unanimous.

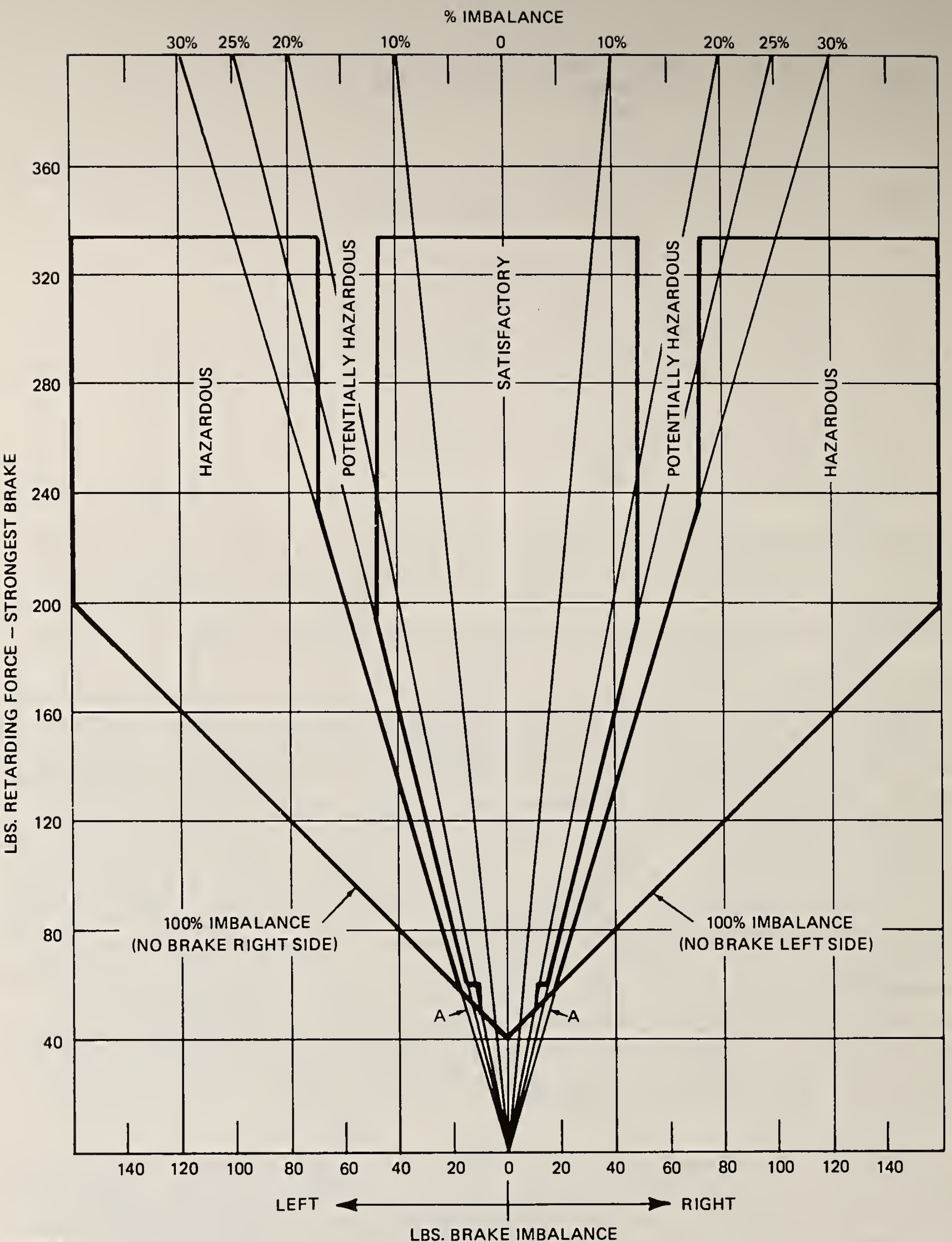

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Figure 3–16 AUTOMOBILE BRAKE EVALUATION STANDARDS (CLAYTON) (Ref. 31)

Some data from HSRI, obtained via Bendix (Ref. 10) shows the levels at which in-use braking is performed (Figure 3-17). From this the requirements for a performance sensor with real-time readout can be derived. On a 3000 lb car, a 0.15 g stop with 20% imbalance would require the sensor to detect force differences on the order of 50 lbs. Because the total effort is 450 lbs, distributed perhaps as 250-200 lbs front-to-rear, the levels of effort involved are comparable to those used on the high-speed Clayton, which has a force capacity of about 350 lbs.

Finally, there is the question of whether a criterion of absolute imbalance or relative imbalance (or both) should be adopted. If absolute, it ought not be expressed in lbs, but as a fraction of the vehicle weight, for example: Absolute force difference between left and right brake shall not exceed 8% of the vehicle weight.

In summary, it is concluded that the functional requirements for a brake performance sensor cannot be determined any more precisely than the current standards for brake performance testing. Whether a sensor can be built that meets any (or all) possible such requirements can only be determined by a test program.

3.2.1.3 Candidate Sensing Techniques -- Brake Performance

No sensing systems capable of meeting the general requirements are currently available. The closest existing candidate is the differential pressure switch (DPS). This device has been widely used to fulfill the requirements of Federal Motor Vehicle Safety Standard 105 (FMVSS-105), for a brake failure warning indicator. The effective date of this requirement was 1968.

Currently available differential pressure switches operate a warning light whenever the pressure difference between sides of the dual hydraulic system (also required by FMVSS-105) exceeds 50 to 250 psi (depending on manufacturer). This permits the device to detect most hydraulic failures arising from leaking seals in master or slave cylinders, broken hydraulic lines, or failure/rupture of other parts (except the master cylinder). It does not, however, detect power boost system faults, loss of friction by contamination, sticking or binding of mechanical parts, or faults leading to excessive braking force at any wheel.

Although it does not fulfill the requirements for a brake performance sensor, the differential pressure switch represents an interesting topic in its own right. It is the only safety related sensor currently in widespread use. Section 3.1.3.1 contains a discussion of the limited information currently available on consumer awareness of the device. There is little information available on its in-service reliability, and on consumer response to failure indications when they occur. A

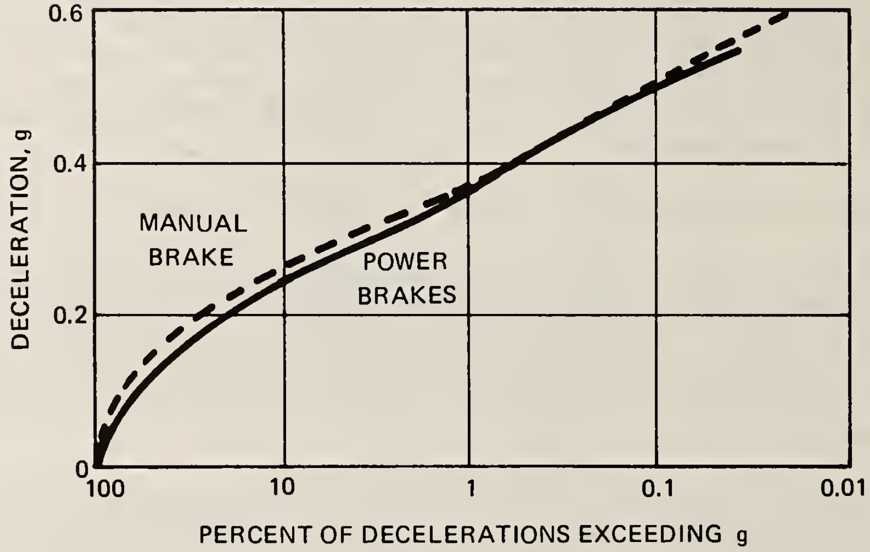

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Figure 3—17 FREQUENCY DISTRIBUTION OF BRAKING DECELERATIONS (Ref. 10)

recent survey of in-use vehicles in St. Louis, Missouri*, however, revealed that of 570 vehicles equipped with the switch, only 7 (about 1.2%) were disconnected, presumably by mechanics servicing the vehicle. Other sources (Title III) have indicated a similar low incidence of lamp continuity failure. However, there is no simple method for determining whether the DPS functions hydraulically or mechanically. This aspect of its reliability is apparently unknown.

As opposed to the DPS, a true brake performance sensor requires measurement of actual braking force and comparing it to a reference. There are two possible independent choices for each:

for braking force:	vehicle deceleration direct force measurement
for reference forces:	pedal load hydraulic line pressure

By combining these possibilities in various ways, four generic types of imbalance sensors can be developed. In addition, there is a fifth possibility obtained by comparing the braking forces among themselves, with no independent reference.

Not all of these possibilities are equally viable. For example, the relationship of vehicle deceleration to braking effort is complicated by power absorption in the drivetrain, the tires, and aerodynamic forces, as well as by vehicle loading and attitude changes. A few simple calculations will show that these effects must be compensated if vehicle deceleration is to be used as the basis for a brake performance sensor. For example, it is easy to vary the load in a full-size (six passenger) car by 1000 lbs. If the nominal weight is taken as 5000 lbs, this represents a ±10% variation in the braking force associated with any specified deceleration. Similarly, grades of ±6% represent another ±10% ambiguity. Finally, aerodynamic forces on a full size car at 55 MPH are on the order of 150 lbs in still air. This number is further increased at higher speeds, against headwinds, or with cargo carried external to the vehicle. Although it is possible to devise techniques which compensate for these effects, it does not appear to be inexpensive. It is concluded, therefore, that brake force should be measured directly.

The difference between line pressure and pedal force as sources of the reference force is that a line pressure transducer would not detect faults in the power booster, nor would it be sensitive to defects in the master cylinder. Since the stresses dealt with at either site are comparable,* pedal force sensing is expected to be comparable in cost to line pressure sensing. Inasmuch as pedal force sensing provides increased diagnostic capability, it is preferred.

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*Safety Status Data Collection Methodology — DOT-HS-01159.

The key to a brake performance sensor is the sensing device - its cost and integration into the brake design. A limited structural analysis (Appendix C) has been performed to assess the probable strain levels that will be produced at the force measuring sections of a typical disc** and drum brake assemblies. The analysis shows that strain levels of 100 to 500 microstrain can easily be developed. This is the range in which semi-conductor strain gages are well suited.

A more direct approach for sensing brake forces in a disc brake system would involve inserting a compression cell between the brake pad and its holder. This would require two sensors per wheel, and would also require the sensors to survive the temperatures produced at that point in the brake system. Under normal conditions, these temperatures are well within the capabilities of currently available semi-conductor devices. However, the maximum temperatures, obtained during fade tests, exceed 600° F, which appears to be beyond current limits.

For a brake design in which the loads can be reacted through compression, a "washer load cell" as depicted in Figure 3-18 would be used to sense the brake force. For a brake design in which the loads are reacted in bending (Figure 3-19) a bolt would be instrumented as in Figure 3-20 to sense the brake forces.

The costs of a transducer for a single wheel are estimated as follows:

1. Load Cell Structure - similar to a dual bellville spring assembly which is a catalog item selling for slightly less than one cent each in quantities in excess of 10,000. (Ref. SPEC catalog B-408).

2. Semi Conductor Strain Gage Bridge with Buffer Amplifier - These specific devices are not produced in quantity, but they can be related in complexity and technology to the National Semiconductor Temperature Sensor Part Number LM 3911 which is now available for 50 cents in quantities of thousands. (When the complexity and technology are compared with mature and highly

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*Line pressure would be greater than pedal load by the mechanical advantage of the pedal and the amount of brake system boost. However, the stress levels are also determined by the physical size and geometry of the load bearing members.

**The disc brake configuration analyzed is not typical of many disc brakes currently in production, because (in the case at hand) loads from the caliper are reacted into the structure by compression. Many designs react the brake loads in shear. New analyses are required for these designs. These calculations are expected to yield similar results.

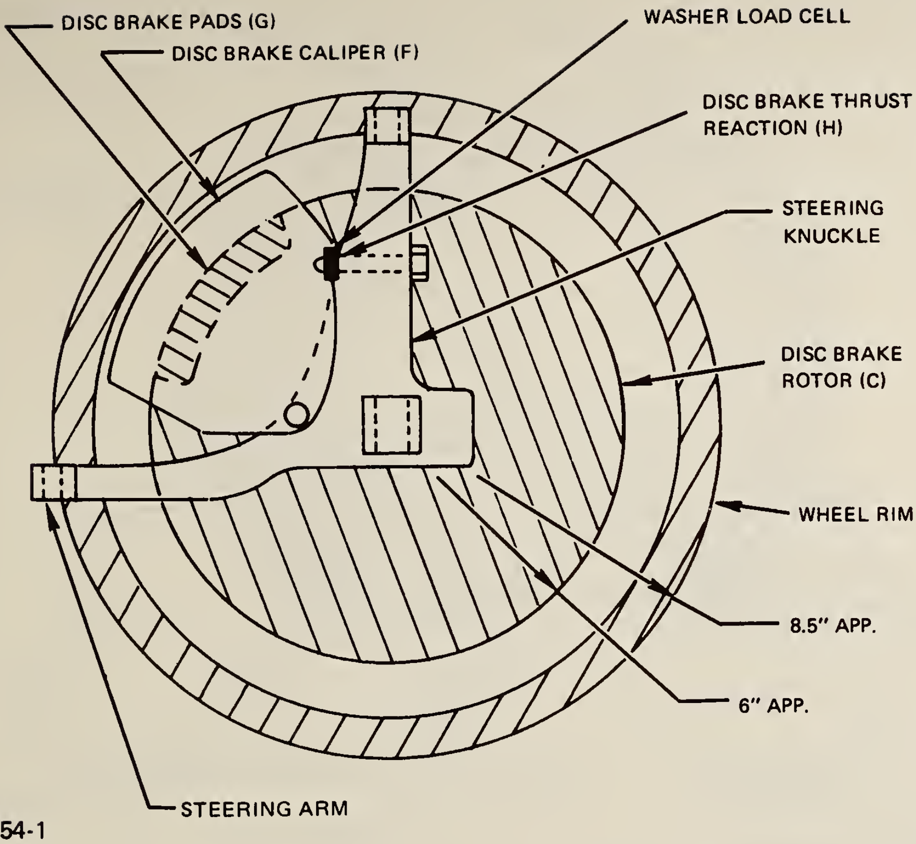

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Figure 3–18 INTERIOR VIEW OF WHEEL AND DISC BRAKE ASSEMBLY IN THE SENSOR

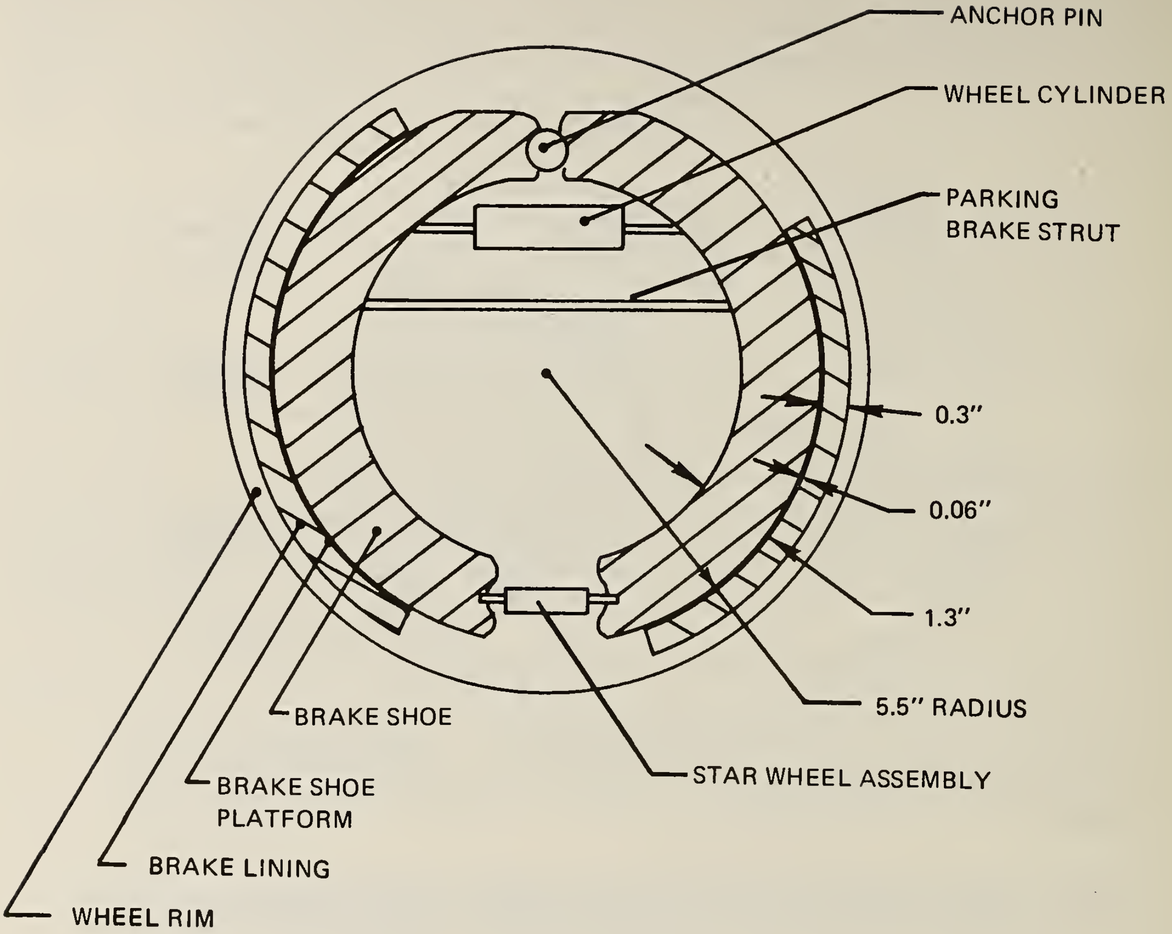

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Figure 3–19 SCHEMATIC OF PRECISION BRAKE MECHANISM WITH SENSOR

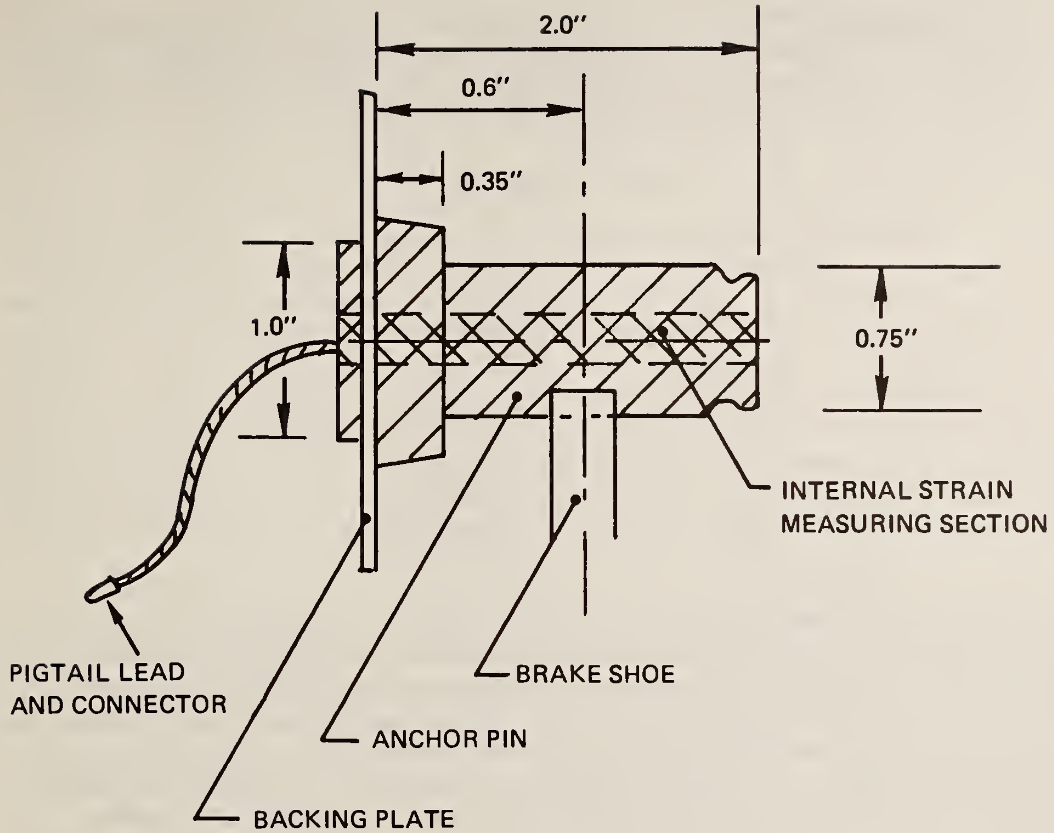

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Figure 3–20 SCHEMATIC OF ANCHOR PIN WITH SENSOR

automated diode and transistor fabrication - reasonably similar processes - there is reason to believe this cost will be reduced by a factor of 2).

3. Miscellaneous Materials - typical 3-pin connectors are catalog priced at less than 20 cents each; approximately 2 feet of 3 conductor lead at 2 cents per foot (4 cents) and potting material at less than 1 cent (Ref. Newark Electronics Catalog No. 102 for the above estimates) yields a total miscellaneous material cost of less than 25 cents.

4. Sensor Assembly - cost estimated at less than 20 cents based on Avco high production (millions) fuse automated assembly line experience in which a device at least 10 times more complex is assembled and tested for less than $1 each.

Thus the total sensor cost to build is estimated at:

Item		Cost
1	=	$.01
2	=	.50
3	=	.25
4	=	.10
Total	=	$.86

If this cost is then doubled (a most conservative estimate) to account for manufacturer's other costs - profit, tooling, design, etc., the total sensor OEM cost to the automobile manufacturer would equal approximately $1.72. Although there is no claim that this is an exacting technique for estimating, there is high confidence that the cost ballpark has been bounded. For this particular sensor, the estimate is fortified by the opinion of two logical candidates for manufacturing these sensors. Two transducer suppliers were contacted to solicit their opinion on the feasibility of producing force measuring devices for less than $2.00 each. I.C. Transducers, Inc. of San Jose, California estimated a cost of $1.00 to $1.50 per sensor in large quantities (this estimate is supported by a letter to Avco from I.C.T.). Endevco of San Juan Capistrano, California also verbally expressed the opinion that a force sensor costing less than $2.00 was realistic. This report uses $2.00 as a reasonable cost estimate.

3.2.1.4 Tradeoff Analysis

Having a transducer for each wheel, there remains the task of integrating them into a sensor/display system. A total of four options have been identified, involving from 2 to 5 force transducers. For each complement of sensors, the possible comparisons are listed in Table 3-17.

The simplest system, A, of Table 3-17 would require logic to compare the outputs from each of the two front wheel sensors and produce an alarm when some differential or brake imbalance is exceeded. A block diagram of the system in Figure 3-21a shows that the two sensor outputs are compared and if the difference voltage exceeds some predetermined value then the alarm is triggered. The problem with using a fixed reference voltage is that as the total braking force increases, the difference voltage will also increase for the same amount of left-to-right imbalance. A level that is set low enough to detect say 25% imbalance at 0.15 g braking will also trigger at 0.3 g with only 12.5% imbalance; thus it must be set to be insensitive at low braking forces or it will produce a high false alarm rate at moderate braking levels -- probably an unsatisfactory situation. The obvious alternative is to use some measure of braking force to produce the trigger reference to increase the allowable absolute imbalance force as the total braking effort increases. This logic is very simple and inexpensive. (Figure 3-21b.) Even with the addition of some filtering circuitry to eliminate sensitivity to noise and very short duration imbalance not representing true brake degradation plus other desired features to deactivate the system below say 0.1 g equivalent brake forces, the single integrated circuit to perform these functions should cost less than $4.00 in large quantities.

A major shortcoming of this system is that it only relates the performance of one wheel against the other. It is unable to detect changes in performance which simultaneously effect both wheels - i.e., loss of gain. By adding one sensor which measures the operator input to the system, say brake pedal force, and using this sensor to develop a voltage which is used not only as a reference for force differences but to establish a reference for proper total braking force, as in Figure 3-22, then front wheel brake gain can also be measured and faulty operation detected.

With the addition of two more force sensors in the rear wheels becomes possible to measure total performance of the brake system and detect all faults that affect performance in a significant way (Figure 3-23). This four wheel plus pedal on-board brake performance measuring system, could replace the differential pressure switch (DPS) used in most automobiles with a far more revealing brake warning system. In fact a four sensor system (Configuration C) could also replace the DPS.

TABLE 3–17. POSSIBLE CONFIGURATIONS - BRAKE PERFORMANCE SENSOR

Configuration	No. of load cells	Location	Comparisons possible	Verbal description
A	2	Front wheels	LF:RF	Side to side, front
B	3	Front wheels and pedal	LF:RF	Side to side, front
			RF, LF, RF + LF: Pedal	Individual or total gain of front brakes
C	4	Four wheels	LF:RF	Side to side, front
			LR:RR	Side to side, rear
			LF + RF: LR + RR	Total proportioning
D	5	Four wheels and pedal	LF, RF, RR, LR: Pedal	Individual gain
			LF + RF + RR + LR: Pedal	Total gain

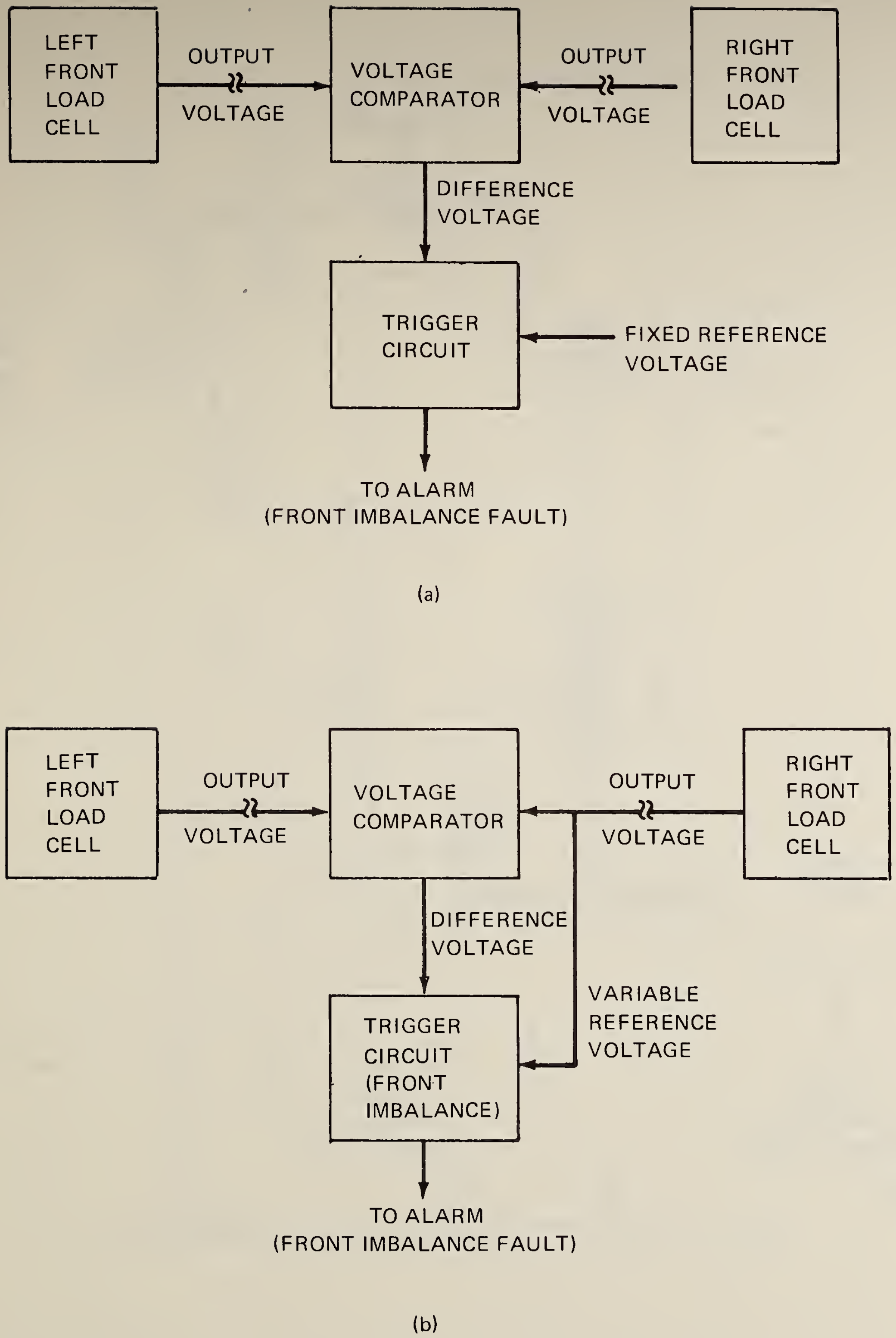

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Figure 3–21 SIMPLE BRAKE PERFORMANCE SENSOR (CONFIGURATION A)

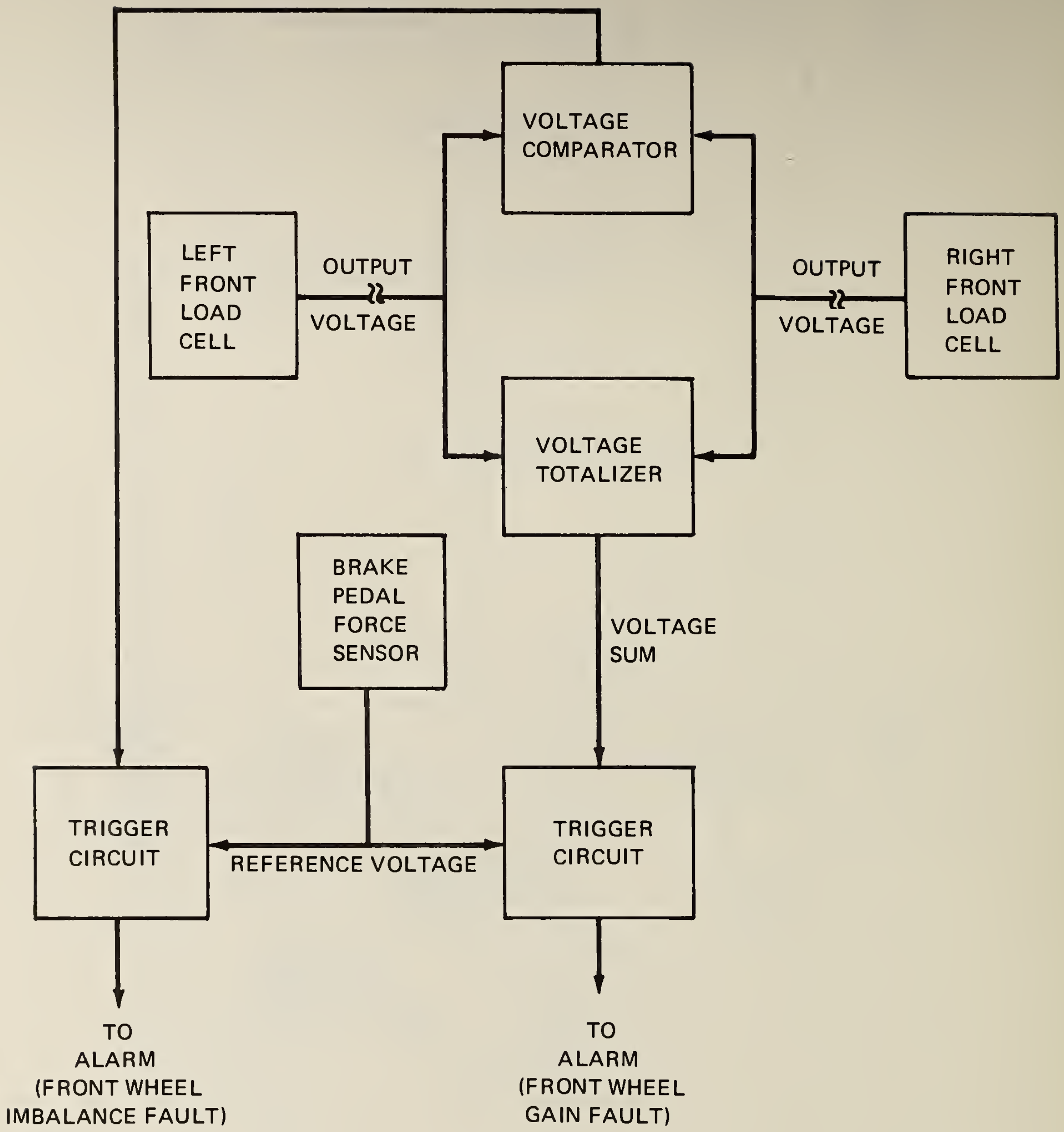

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Figure 3–22 BRAKE PERFORMANCE SENSOR (CONFIGURATION B)

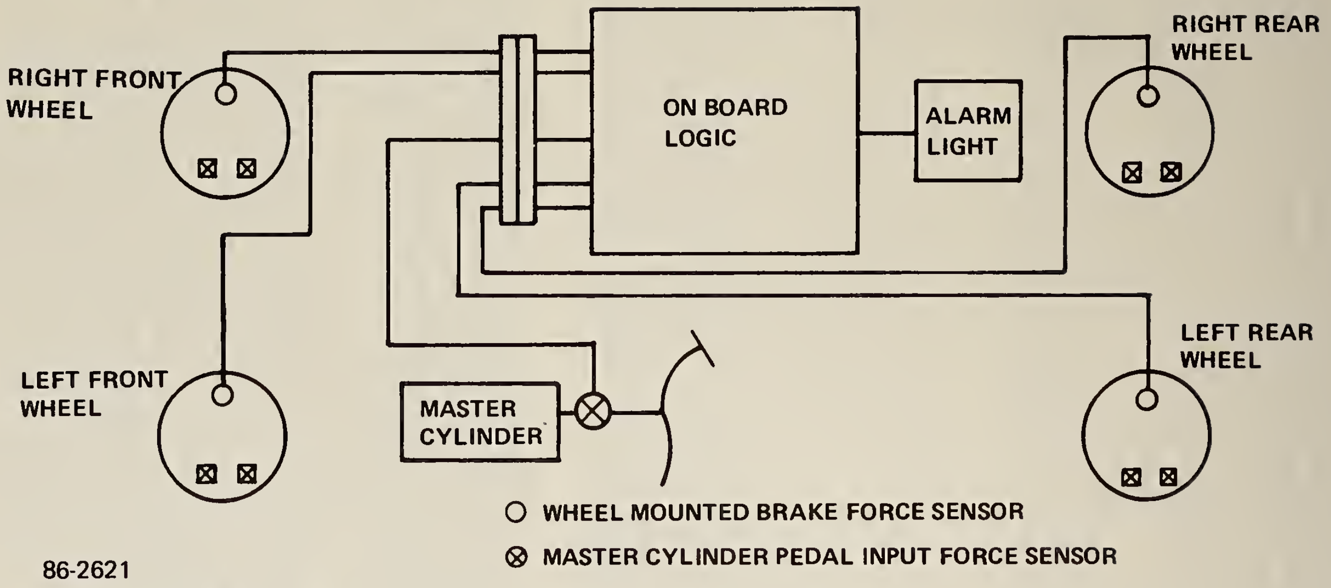

Figure 3–23 BRAKE PERFORMANCE SENSOR (CONFIGURATION D)

Cost estimates for each of the performance sensor concepts are developed in Table 3-18. To aid in trading-off the configurations, a review of the Indiana brake data has been conducted to localize the faults indicated. The results follow:

	No. of cases	No. of cases unaware	Indictment total	Indictment total (unaware cases only)
Problem in front brakes only	7	5	4.72	3.57
Problems in front and rear brakes	7	3	4.36	1.67
Problem in rear brakes only	4	4	1.27	1.27

Although the data are somewhat sparse, they conform to the expected trends. Rear brake difficulties tend to be less often detected than front problems, and problems at both ends of the vehicle tend to be more detectable than problems at the front only.

If this data is taken as representative, we compute that 88% of the total indictment, and 51% of the undetected indictment can be associated with vehicles having a problem in the front brakes. If the potential payoff for Configurations A and B are recomputed on this basis, one obtains $113 in total accident benefit (88% of $129) and $65 in potential benefit for the unaware cases only (51% of $129).

Considering economic benefits, it is probably unreasonable to expect a significant savings in disc/drum refinishing, since a performance sensor will (at best) detect metal-to-metal contact only after it has become bad enough to cause braking problems. On the other hand, a fraction of the disc/drum replacement cost may be recoverable. Taking 35% as an estimate, we obtain (in round numbers) $11.00. This is half of the replacement savings postulated for pad/lining wear indicators. Dividing this equally between fronts and rears, the picture becomes:

Configuration	Maximum safety benefit	Maximum economic benefit	Total
A	$113	$ 6	$ 119
B	113	6	119
C	129	11	140
D	$129	$ 11	$ 140

What about periodic inspection of brakes? A thorough brake inspection -- involving both wheel removal and performance inspection is quite expensive. Table 3-10 develops a cost estimate of about $6.50/year for semi-annual performance inspection and removal of two wheels. Over 12 years, this represents $78, exclusive of increased costs to the vehicle owner for brake repair.* The cost benefit tradeoffs are illustrated in Figures 3-24 and 3-25.

In Task 2, it was determined that the concept of brake performance sensing should also be evaluated for implementation in an off-board readout mode, using additional interface equipment. In this mode, a brake performance sensor is functionally identical with a dynamic brake machine.

For a brake performance sensor with off-board readout, components on-board the vehicle would probably be limited to the sensors and wire needed to reach a central connector that mates with the interface equipment. Costed according to the groundrules used for the version with on-board readout, a five sensor system would have a lifetime cost of $36, which is about half that of its real-time counterpart. For such a system, the most plausible means of performing a test would be by means of portable interface equipment used during a short road test. Testing the vehicle in a stationary fixture (such as a set of rollers) would require essentially the same mechanicals as a brake test machine (power absorption capability, but not force measurement) and would greatly increase costs.

Providing all the labor costs, building costs, and costs to the owner are the same for interfacing with the on-board sensor as they are for using the self-contained test machine, the on-board sensor with off-board readout costs significantly more than the self-contained machine. The $36 initial cost is prorated over 12 years yielding an annual cost of $3.00. Table 3-9 shows an annual equipment cost of $.46 for currently available commercial brake test equipment. This figure applies to equipment installed in a lane/bay inspection facility servicing 8,850 vehicles per each two pieces of test equipment (one installed in lane-performing initial inspections, one in a bay - performing reinspections). Semi-annual inspection is assumed. If the machine were an order of magnitude less utilized, or an order of magnitude more expensive, the rating of the two systems would be reversed. However, it should be noted that a lower-cost brake test machine is currently under development for NHTSA.** If the objectives of the program are realized, the cost balance will shift toward off-vehicle inspection equipment still more strongly.

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*These have also been dropped from the sensor evaluation as well. (See discussion of "compliance costs" in Ref. 26.)

**Manual Brake Inspection Procedures, DOT-HS-5-01188.

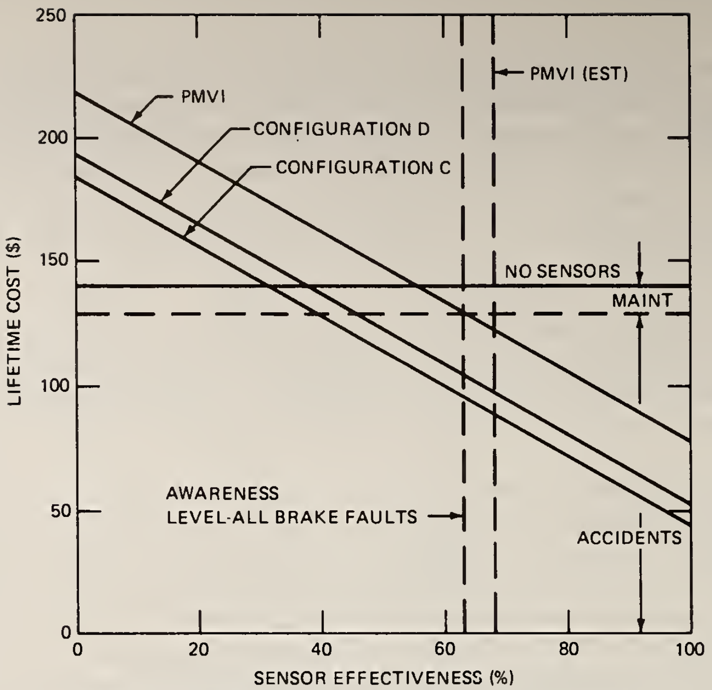

Figure 3–24 COST BENEFIT TRADEOFFS TWO WHEEL BRAKE PERFORMANCE SENSORS

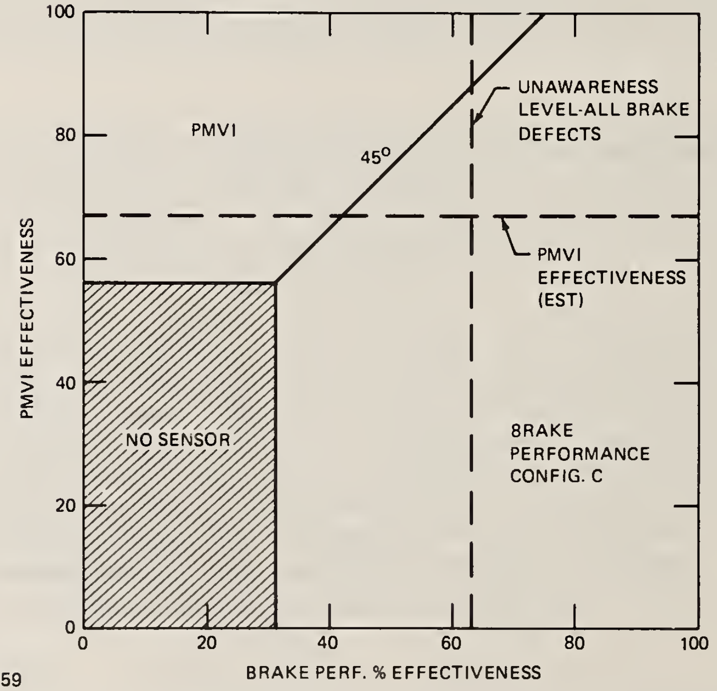

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Figure 3–25 COST BENEFIT TRADEOFFS FOUR WHEEL BRAKE PERFORMANCE SENSORS

TABLE 3–18. BRAKE PERFORMANCE SENSOR COSTS

OEM Cost Estimates

1. Load cell sensor (complete with connector and 2 ft. wire pigtail)	$2.00
2. Imbalance logic module (compares output from sensors and drives display with off-board diagnostic connector)	
A - 2 sensor comparator	$4.00
B - 3 sensor comparator	4.50
C - 4 sensor comparator	5.00
D - 5 sensor comparator	5.50
3. Display (not counting modification to dashboard and supporting structure)	$1.00
4. Interconnecting cabling and connectors	
A - 2 sensor system (20 ft wire)	$1.00
B - 3 sensor system (20 ft wire)	1.00
C - 4 sensor system (50 ft wire)	2.00
D - 5 sensor system (50 ft wire)	2.00

Total System Cost

	OEM	Markup (OEM x 3)	Maintenance @ 20%	Total cost of ownership
A - 2 sensor system	$10.00	$30.00	$ 6.00	$36.00
B - 3 sensor system	12.50	37.50	7.50	45.00
C - 4 sensor system*	16.00	48.00	9.60	57.60
D - 5 sensor system*	18.50	55.50	11.10	66.60*

*These sensors could also replace the DPS, now commonly used to detect partial system failures, with an additional lifetime savings estimated at $14.00.

3.2.1.5 Recommended Configurations

The cost-benefit analyses show that a brake performance sensor with on-board readout is competitive with periodic inspection at comparable levels of effectiveness. As mentioned repeatedly, the effectiveness of either measure is highly uncertain. It should also be clear that the choice between the different performance sensor configurations is impossible to make on the basis of the available data.

It is Avco's opinion that the single most promising on-board sensor development activity is the brake performance measurement system. It offers a greater accident reduction potential than any other sensor, as well as the possibility of maintenance benefits to the automobile owner. There is every indication that the hardware could be developed without great difficulty. There are, on the other hand, significant problem areas that must be resolved before practical feasibility of the technique can be established.

The real issue is - Is it possible to establish realistic fault criteria that can be reliably sensed and used for on-board fault indication?

For example it remains to be demonstrated that the brake performance faults which cause a critical stopping or handling problem during high speed panic braking will manifest themselves as detectable faults at low braking levels when the warning must be sensed. Many faults, such as loss of hydraulic fluid, will certainly be evident regardless of braking level, but others, such as brake lining contamination may not. The ability of the system to adequately warn of faulty brakes is dependent upon understanding this.

On the other hand, is it possible that brakes often perform erratically or poorly at low braking forces and vehicle speeds, when it matters little, but then perform adequately for high speed panic stopping. For example, slightly sticky caliper assemblies might produce a large percentage imbalance under low hydraulic pressure but that same caliper assembly might perform adequately when forced hard by high hydraulic pressure. Should such conditions occur with any frequency then the false alarm rate could become unacceptably high.

Until significant additional work is done, however, conjectures as to the feasibility or infeasibility of a brake performance sensor will be simply that - conjectures.

3.2.2 Tire Inflation Sensor

3.2.2.1 Review of Justification

The Indiana data identified tire inflation as the second most important candidate area for sensor application, and the most important candidate area based on a single cause of defect related accidents (as discussed previously, the brake imbalance sensor has the capability of detecting a variety of faults). The general relationship between tire inflation and degradations in vehicle handling have been corroborated in laboratory studies. It would appear that tire inflation is qualitatively non-controversial as a contributor to defect related accidents. The only questions concern the magnitude of the effect.

In addition to accident reduction (caused by degraded handling due to underinflation) there are other significant reasons for considering underinflation sensors; reduction in blowouts (most blowouts are preceded by operation below rated pressure), plus operator cost savings and energy conservation through improved gasoline mileage and reduced tire wear.

Another potential motivation for incorporating tire inflation sensors on automobiles is created by the possibility that spare tires may be eliminated on automobiles some time in the not too distant future as a move to improve mileage through weight reduction and make available for more productive uses the space that is now lost to spare tire and car jack storage. Several tire and automobile manufacturers are working on concepts which allow the car to be driven for a significant distance (the goal seems to be 50 miles at 50 miles per hour) on a secondary support system built into the tire after the main air cavity has lost its pressure. If running on the secondary system is as smooth as hoped for then it will be necessary to indicate the loss in primary air pressure to the driver. Otherwise, he may unknowingly continue to operate on the secondary support system until it too deteriorates to the point where he is forced to stop thereby defeating the purpose of the secondary system.

3.2.2.2 Functional Requirements

The most basic concern is the determination of an appropriate threshold at which the sensor should give a fault indication. Reference 5 recommends that inspection limits for inflation pressure be ±1 psi from manufacturer's specifications. John Diehl (NHTSA) has indicated that 5 psi under pressure is the threshold of vehicle handling concern. The Indiana investigators were reluctant to indict tire pressure unless the deviation was about 8 psi below specifications. (Figure 3-26.) Over pressure, as shown by these data, is a negligible contributor to accident causation. Detailed consideration of vehicle handling characteristics indicates that it is the balance between inflation pressures

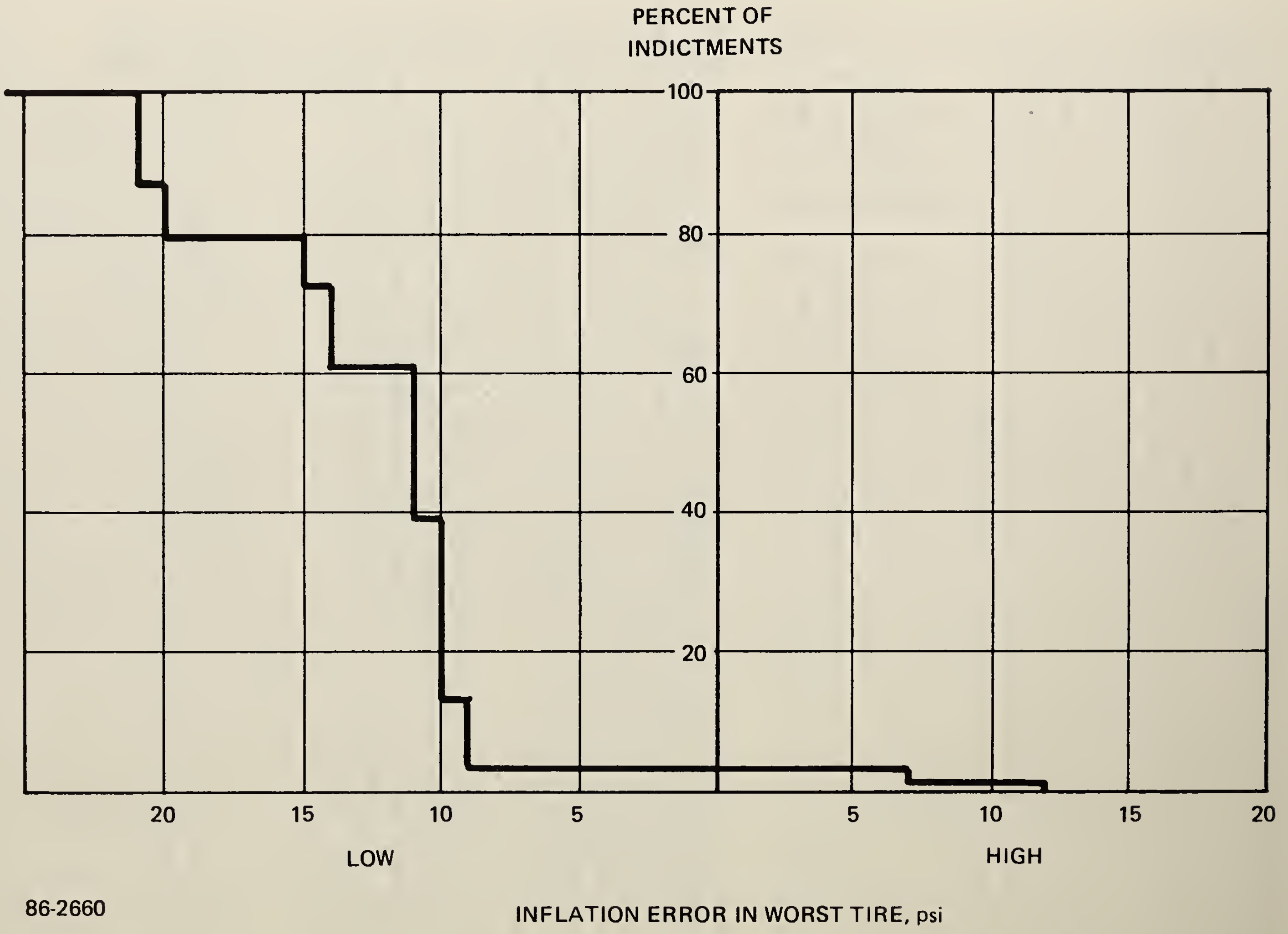

Figure 3–26 INDIANA RESULTS ON MAGNITUDE OF INFLATION ERRORS

front-to-rear and side-to-side) that can affect handling about as strongly as the inflation level at any specific tire (Ref. 5). This is, setting front inflation 3 psi high and rear inflation 2 psi low will have about the same effect as having nominal inflation at the front and 5 psi low at the rear. In addition to balance, there are other factors to be considered. The normal inflation pressure, for example, ranges from a high of 32 psig (Plymouth) to a low of 22 psig for some GM autos. Further, overloading a vehicle could cause the same danger as under inflation. One can only choose a sensor threshold and hope that it covers the problem adequately. For purposes of this report we shall assume that the sensor threshold is 5 psi below nominal.

3.2.2.3 Candidate Techniques

Unfortunately, warning the operator of low tire pressure on a moving automobile presents a very difficult problem that is not easily solved with low cost hardware. There are two significant technical problems that must be overcome - first, sensing the underinflation with reasonable accuracy and second, relaying this information from the rotating wheel to the car chassis. Neither would be a serious problem if cost were not a factor. It is quite clear, however that the the OEM cost of all equipment for a four wheel sensing system should be less than $25 and then it must have very low maintenance costs if it is to be cost effective and have any real chance for public acceptance. Many companies have invested large sums of money developing tire pressure sensors. Table 3-19 is a partial list of these companies, but none has succeeded in penetrating the automobile market with these devices. Many sensors have been tested on automobiles including the installation of several Goodyear, Winther and Tyrechek systems on GSA vehicles under contract to DOT, but none of the tests conclusively demonstrates a concept proven for widespread use.

TABLE 3-19. DEVELOPERS OF TIRE INFLATION SENSING SYSTEMS

Tyrechek
General Motors (AC)
Tora Flite
Uniroyal
Magnavox Magna-Miler
Bendix
Pin-Ray
Schraeder
Vedyne Tirometer (ITT Electronics)
Michelin/Jaeger
TRW
Plessey Dynamics
Michelin
Nissan, Japan (Datsun)
Heenan Aspa, England
Winther
Bridgestone, Japan
General Motors (Delco Div.)
Goodyear

The obvious technique for sensing underinflation (and the method used by most of the systems that have been tried or are under development) is to mount a pressure sensor inside the tire or outside and attached to the tire valve stem. Because of the difficulty in supplying continuous power to the rotating wheel, which could be used to electrically establish the alarm trip point, most pressure sensors are designed to mechanically trip or unlatch when tire pressure goes below a predetermined value. This feature compounds the difficulty of producing a low cost sensor which is typically required to trip at say 5 psi below normal inflation pressure and yet not trip on 3 psi underinflation (a tolerance band of some ±5%) while exposed to temperature variations ranging from -30^{o} F to approximately 250^{o} F (typical temperatures in an underinflated tire running at high speed), acceleration ranging from 0 to well over 50 g's, vibration, shock, water, dirt, etc., with little or no maintenance and a mean time between failure in excess of 10 years.

Although there are no fundamental physical reasons why this cannot be achieved, there must be serious doubts about ever achieving these goals with reliable low cost sensing systems.

Given that the underinflation signal has been generated, the problem of transmitting the signal to the automobile at low cost is almost equally difficult. Innumerable techniques have been considered and many developed to solve this problem. The uniqueness of most of the more than 50 patents issued for tire inflation sensing systems pertains to techniques for coupling between the rotating wheel and non-rotating automobile chassis. A brief discussion of some of those concepts and their pro's and cons will give an idea of the scope of this problem.

Perhaps the most obvious approach is to utilize a slipring (functionally similar to the commutator on an electric motor) in which a brush assembly mounted to the moving wheel rides against a slipring mounted to a non-rotating wheel member. This is the concept used by TORA-FLITE who has had substantial experience with development systems installed on trucks and recreational vehicles. Although the system may be cost effective for certain applications such as trucks, it does not appear practical for general automobile use. There are a set of problems associated with this concept; among them are:

1. the slipring must be mounted concentrically with the wheel and in a relatively protected area limiting its placement to say on the backing plate or within the axle (a difficult wheel redesign and production line installation problem would almost certainly result).

2. reliable operation for 100,000 miles over 10 years would probably be difficult to achieve because although the brush/slipring assembly will no doubt operate this long under ideal conditions, any abrasion contamination can dramatically reduce this life and it is doubtful that all contamination can be prevented even in so-called sealed assemblies.

3. the brush assembly must either be removed with the wheel or disconnected as the wheel is removed and the potential for damage during routine tire changes, brake maintenance, etc. would be difficult to overcome. The concept does offer the advantage of making it possible to provide electrical power to the wheel mounted sensor and it will function with the vehicle stopped.

Many concepts have been developed for electrically coupling an underinflation signal from the wheel mounted transducer to the chassis without sliprings. In general, the concepts are similar in that underinflation sensed by the transducer is used to open or close an electrical circuit which rotates with the wheel. (See Figure 3-27.) This rotating circuit is electromagnetically coupled with a stationary circuit. When the state of the rotating circuit changes due to actuation of the pressure sensor, the fixed circuit is altered in a way that is sensed by on-board logic and the low pressure alarm actuated. The Vedyne Tirometer and Goodyear systems which have both been developed and treated are among the many companies which have worked with this concept. Although this technique eliminates wear and precision alignment problems of direct contact between brush and slipring, it still retains the disadvantages of a concentric, close and controlled relationship between one component mounted to the rotating wheel and another fixed to the stationary part of the wheel assembly. It also requires a more complex electrical circuit which must detect relatively small changes in the electrical characteristics of the fixed circuit - a generator and frequency, phase or amplitude detectors are typically required. Vedyne is planning to market systems for truck use at an uninstalled cost of some $400 for an 18 wheel truck. Clearly this per wheel cost is too high for the automotive market.

Another technique that has been extensively developed (by General Motors and the Winther Corporation) places a pressure sensitive valve on the tire stem or, in the case of the GM system, in the wheel rim. When the tire pressure drops below a set point, the valve opens sending a pulse of air pressure through a tube to reposition a spring loaded plunger. (See Figure 3-28.) The metallic plunger moves closer to a sensor which now detects the plunger passage every time the wheel rotates and actuates the underpressure alarm. It is, of course, possible to use a plunger to mechanically contact a switch for alarm actuation. This concept somewhat simplifies the electronics from those used in the previous concept for a more positive high amplitude signal can be generated which is

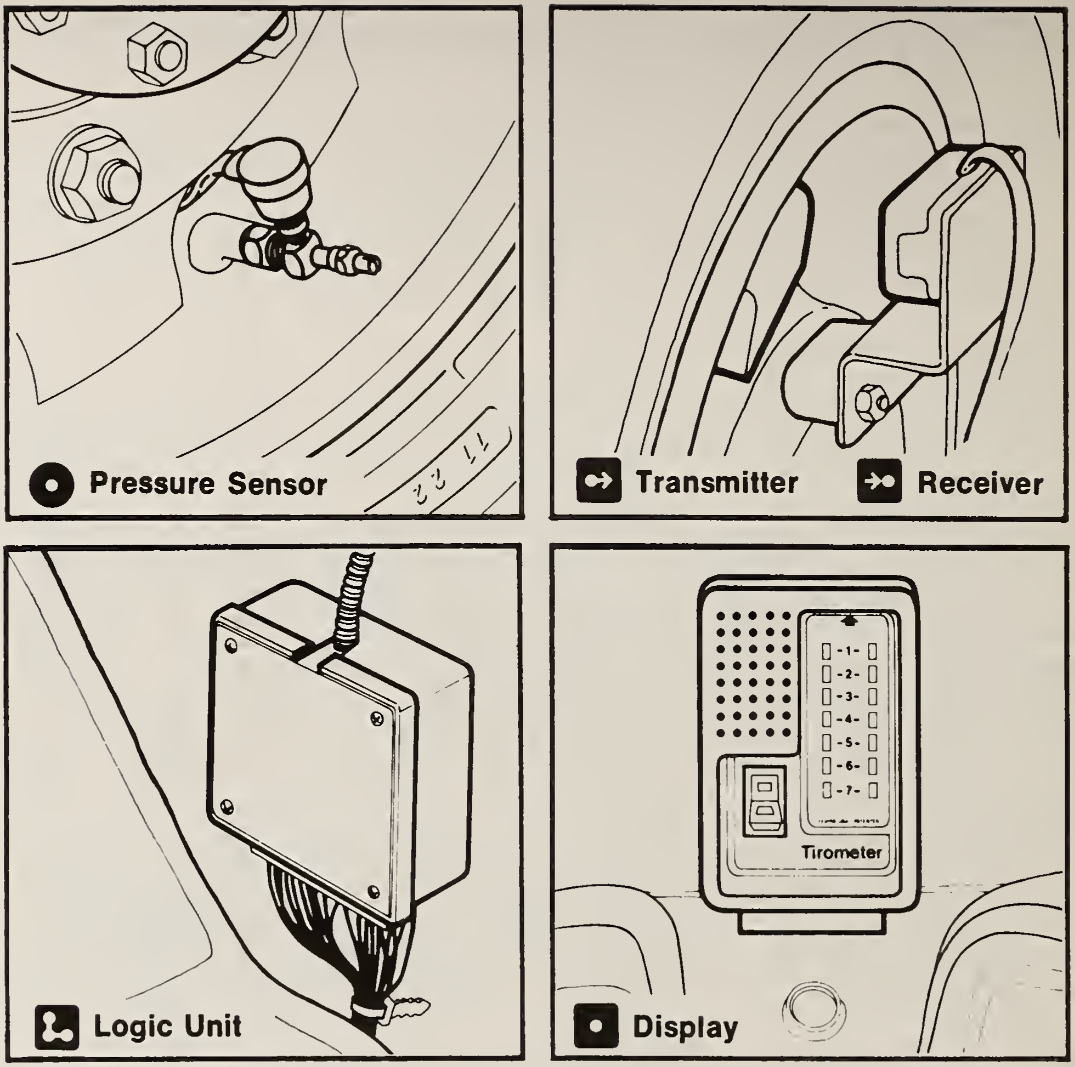

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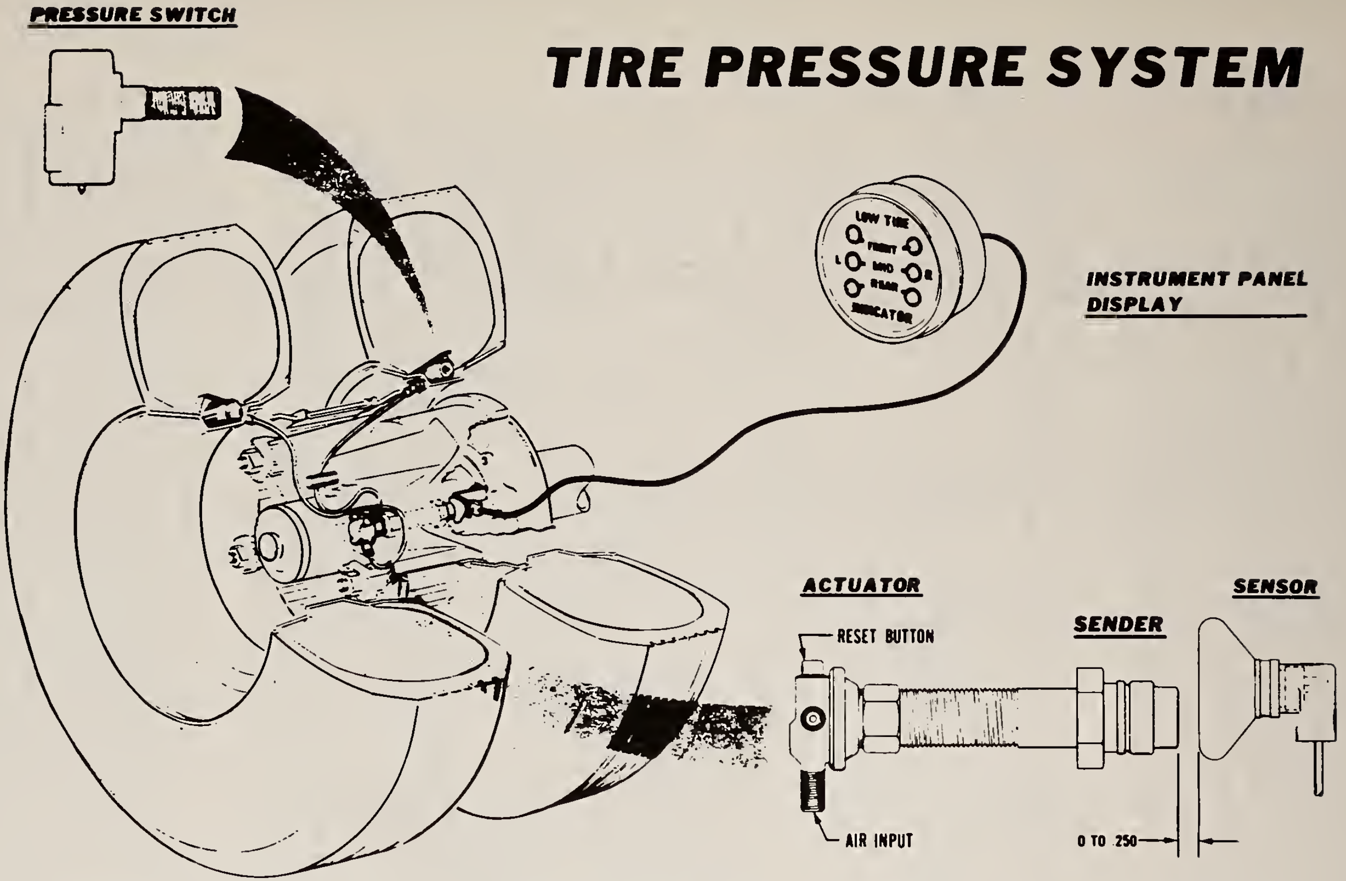
Figure 3–27 COUPLED ELECTRICAL CIRCUITS (VEDYNE TIR-O-METER)

TIRE PRESSURE SYSTEM



PRESSURE SWITCH IN THE TIRE DETECTS LOW PRESSURE AND SENDS TIRE AIR TO ACTUATOR

ACTUATOR TURNS ON SENDER WHEN TIRE AIR PRESSURE IS LOW

SENDER SIGNALS SENSOR

SENSOR DETECTS SENDER SIGNAL AS WHEEL ROTATES

INSTRUMENT PANEL DISPLAY ALERTS DRIVER OF LOW TIRE PRESSURE LOCATION

86-2662

Figure 3–28 AIR ACTUATED PLUNGER (GENERAL MOTORS)

easily detected and free from the radio interference problems that can exist with the other systems. On the other hand, the tubing required to transmit air pressure to the plunger and the plunger itself are significantly more costly to produce and install than wire and coil. It is impossible to make generalized cost and effectiveness comparisons between pressure sensitive switches and pressure sensitive valves. The OEM cost for a system has been projected by GM spokesmen to be in excess of $300 for an 18 wheel truck (they are not planning to market this system for automobiles), again too expensive for consideration in automobiles.

The one developed approach which seems to come closest to meeting the low cost automobile needs is that in which the underinflation signal is transferred from the rotating wheel to the automobile chassis by means of a radio transmission link. (See Figure 3-29.) This device is included in one of the display models discussed in Section 4.0. (See Figure 4-2.) In this concept, a small module containing a pressure sensor, radio transmitter and dry cell storage battery are mounted in or on each wheel. When the tire pressure goes below the set point, the pressure sensor closes a switch which applies battery power to the transmitter which then transmits a tone. Typically, a receiving antenna mounted to the chassis near each wheel sends the signal to a centrally located receiver which energizes the underinflation alarm. Although there are plusses and minusses in the cost comparison between this technique and the others, the overall hardware costs should be somewhat lower (one supplier, TYRECHEK, believes they could deliver 4-wheel automobile systems for approximately $30 OEM which looks to be substantially lower than any other well developed concept) and perhaps more importantly the installation cost should be significantly less. Even with these cost advantages there is significant doubt that these systems will prove to be cost effective. Furthermore, there are maintenance and reliability issues that must be thoroughly evaluated before their effectiveness and lifetime costs can be defined. For example, will the batteries have a 3-year storage life under all the environments? Will they perform satisfactorily at the temperature extremes? Is a 3-year storage life adequate especially with tire mileage increasing? Is the false alarm rate due to radio interference satisfactorily low etc., etc.?

There is another family of tire inflation sensors which are typically mounted on the tire valve stem and which gives a visual indication of inflation state. Some such as the Engler Instrument Companies "Indicap", produce a continuously visible indicator when the inflation pressure is low while GM sells a sensor which has a protective cap over it and will indicate the tire inflation pressure, in psi, when the cap is removed. Of the two, the continuously visible sensor is a far more effective low pressure warning device but that type has a reportedly high failure rate. GM supposedly achieves a lower failure rate by convering their sensor up except for when it is being read. (Figure 3-30.) There may well be a

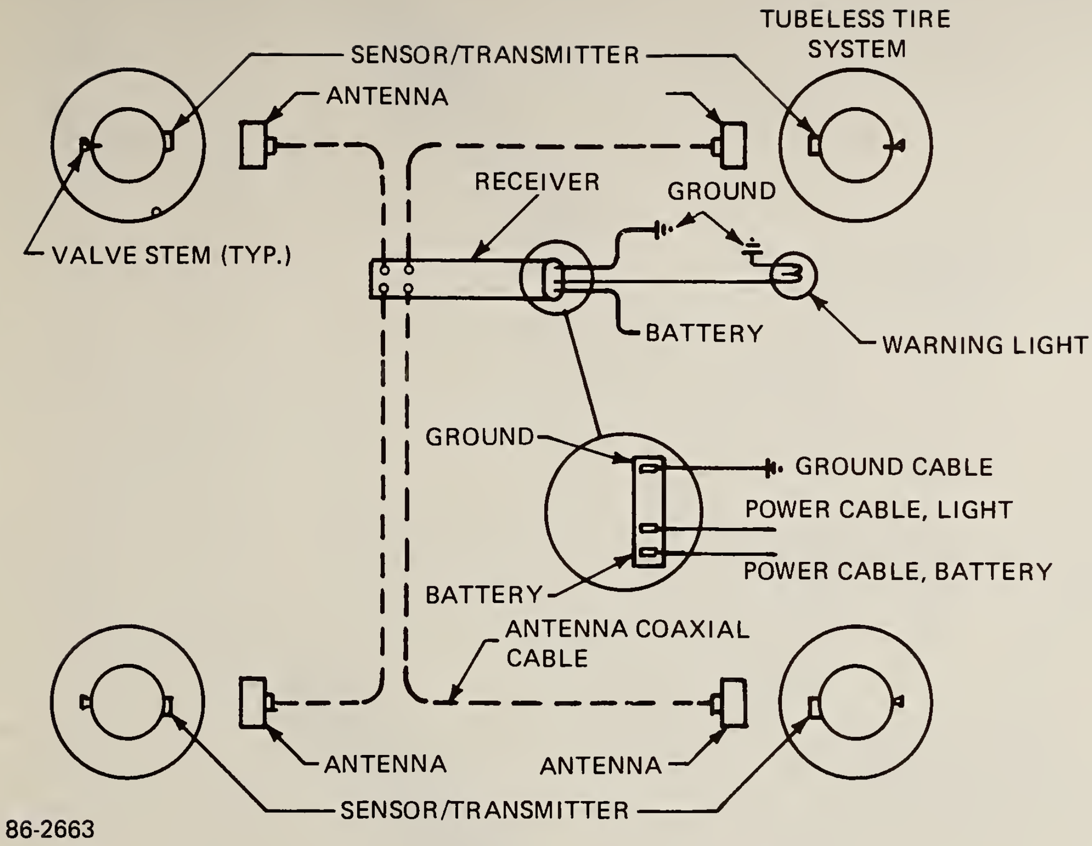


Figure 3–29 BATTERY POWERED SENSOR/RADIO TRANSMITTER

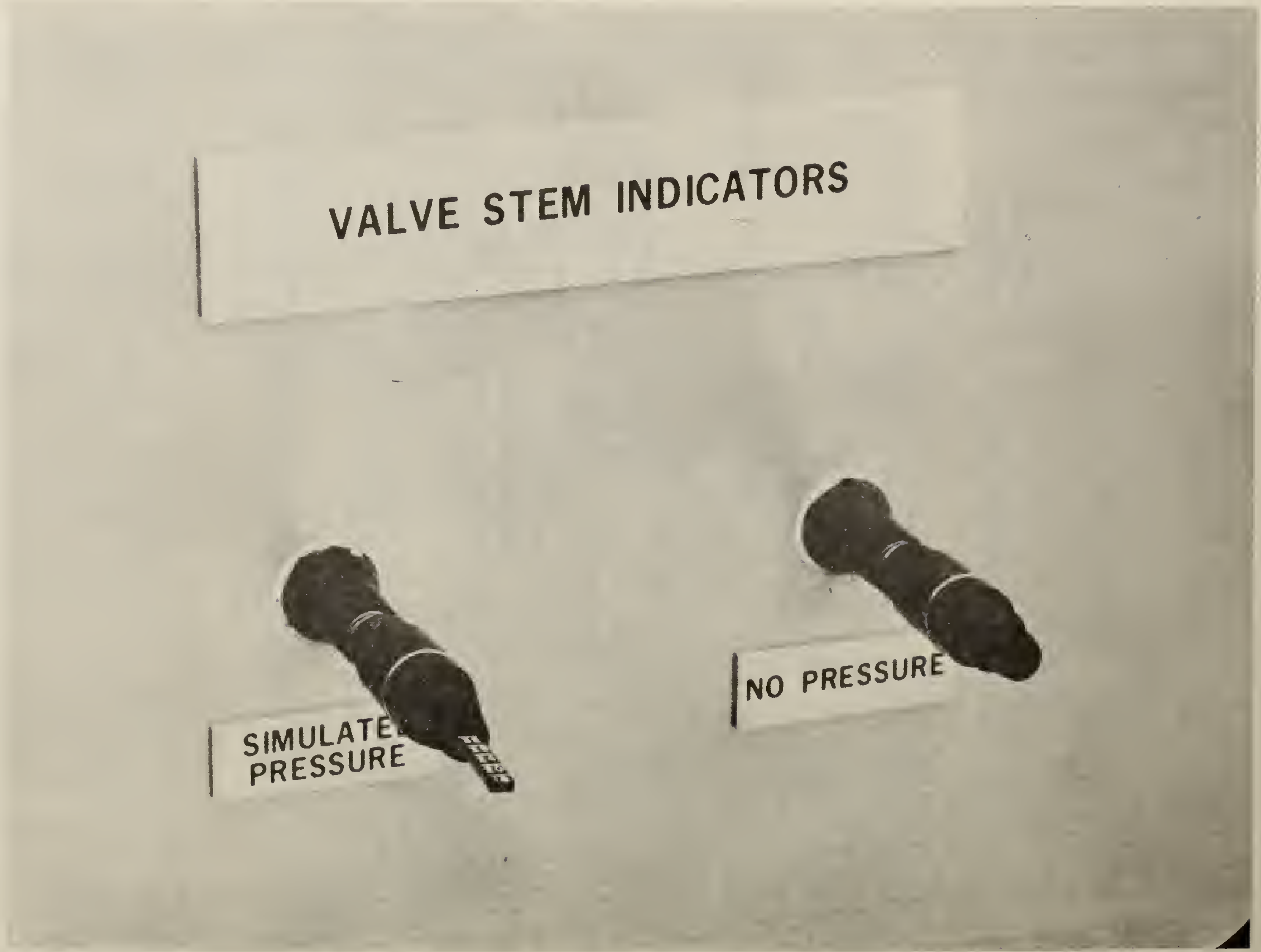


Figure 3–30 GENERAL MOTORS TIRE INFLATION SENSOR

place for these low cost indicators for although they are far less effective than the more complex sensors previously discussed (they give no warning to the driver when the car is being operated and they are of value only to those people willing to walk around the automobile, and remove the cap on the GM device, and observe the sensors with some degree of regularity); they are much less expensive (retail cost generally under $3.00 for a set of 4); and may turn out to be the only system that is low enough in price to be publicly accepted.

Uniroyal, a major tire manufacturer, has developed a very simple low cost device for low tire pressure sensing. It consists of a double spring-loaded probe, suspended from the axle beside each of the car's wheels. When tire pressure drops by six or seven pounds, the probe touches the road. This activates a switch that sends current to a capacitor, part of a standard timing circuit using a unijunction transistor. When the capacitor has charged to a minimum voltage level, the unijunction turns on a silicon-controlled rectifier, which sounds an alarm on the dash. The alarm won't sound, however, unless the probe maintains contact with the road for 10 seconds. The reason: to keep momentary bumps from triggering the device. There's also a manual override to turn off the device if you're driving over snow-covered roads, where contact would be continuous.

There is a serious question of the ability of a device such as this to function reliably throughout the normal lifetime of an automobile. Designing a probe that will not be shortened by abrasion of the tip as it repeatedly strikes the road at high speed and will not fail due to the repeated shocks, may well be unachievable.

Another concept which was briefly investigated under this study and also has the potential for producing an underinflation system at an acceptable price utilizes the tire itself as the pressure sensing mechanism, and the rotating wheel as an energy source for producing the underinflation signal. The tire is essentially a balloon (albeit a stiff one). Thus, its cross section changes with variations in internal air pressure. If magnetic material is bonded to the sidewall and an inductive probe, which generates a voltage when a magnetic field passes by its sensitive end, is affixed to the vehicle chassis (say the wheel backing plate) in such a way that its sensitive end is in close proximity to the passing magnetic material, then a voltage will be generated in the probe that is a function of the distance between the magnet and probe end. This distance will change slightly as the tire internal pressure changes and cause the output from the sensor to change in amplitude. The output amplitude is also a function of wheel velocity. However, this can be cancelled out by placing another magnet in a location that is not displaced with changes in tire pressure (say on the wheel rim), but rotates at the same speed (this cancellation is aided by the fact that output changes linearly with speed and with the square of tire distance). By utilizing the second magnet as a reference it is also possible to cancel out positional changes in the probe. This concept, by eliminating the need for a pressure sensitive transducer and by utilizing passive components for removing the signal from the tire, will not need those elements which are most costly to procure, are most subject to failure, and which will cost the most to maintain. Thus, it has a potential for cost effectiveness that no other known technique appears to have.

On the other hand there are some very significant technical obstacles which must be resolved before feasibility and practicality can be truly measured. For example: the tire deflections are not large except at the bottom where the probe would be subjected to a severe environment (although if the tire sidewall can survive its environment it should not be too difficult to design a probe that can survive); each tire style, type and installation would be different thus it would be necessary to make sensitivity adjustments for each installation; magnetic materials would have to be affixed to all tires (a logistics problem more than a technical or cost problem); and compensation for speed and probe movement effects will be far from 100% perfect and could introduce errors that are impractical to accept.

Despite these problems, the rather brief analysis of the concept and some limited test results have been encouraging. It is recommended that additional development effort be applied to this concept to determine its practicality.

A review of all of the tire underinflation sensing systems either available or under development indicates quite strongly that the concept utilizing a battery powered transmitter in the tire is probably the lowest cost technique for an underinflation system which can be realistically considered at this time. The effectivity of valve stem mounted visual indicators is too much in doubt to be seriously considered prior to a thorough effectivity study. Accuracy, reliability and longevity of the Uniroyal concept would have to be demonstrated through extensive road tests before this technique could be considered. The magnetically coupled concept conceived by Avco must have much more development if it is to be proven practical. The performance capabilities of these inherently lower cost techniques are not only too uncertain to be promoted, but estimating their costs (except for the visual indicators) is also very difficult.

Discussions with the TYRECHEK Corporation, producers of a battery powered transmitting device, disclose that the OEM cost for a system (minus interconnecting cabling) would be approximately $30 in quantities of millions.

Applying the factor of 3 for manufacturer's mark-up brings the cost to $90.00 on the automobile purchase cost.

Batteries are a consumable with a life estimated (by TYRECHEK) of between 3 and 5 years.

For the existing system, battery replacement requires breaking the tire beads away from the rim. This would be acceptable, providing the battery lasts as long as the tire, and is replaced at the same time the tire is replaced. Although 3 years is somewhat short, replacement at four year intervals would mean 3 sets in the life of the car. At a projected cost of 40 cents per battery, this would add about $5.00 to the cost of ownership.

It is estimated that due to system complexity and location of transmitters within the tires that 100% of initial cost would have to be applied for maintenance or $90.00.

Total estimated lifetime cost:	$ 90.00
	5.00
	90.00
	$185.00

3.2.2.4 System Tradeoffs

Even for the least expensive practical system, the cost benefit analysis is somewhat unfavorable. The maximum potential benefits (Tables 3-5 and 3-7) are:

Reduced accidents	$39.11	→	$39.00
Economic Savings			
Fuel Economy	8.00		
Tire Wear	14.40		
Tire Failure (50% of all failures)	5.20		
Economic Total	$27.60	→	$28.00
Grand Total			$67.00

Comparing this with the estimated lifetime cost of $185, it is clear that a major cost breakthrough is required.

3.2.2.5 Recommendations

It is clear from the Indiana study results that tire underinflation sensors could be of substantial value in reducing automobile accidents.

Unfortunately, study has concluded that the cost of implementing underinflation sensors far outweigh the benefits utilizing existing sensor technology. The following recommended activities are aimed at improving the benefit cost ratio to the point that on-board tire inflation sensors can be justified.

1. Promote development of underinflation sensor system techniques that show promise of being significantly less expensive - concepts such as the magnetic coupling sensor conveived by Avco and possibly the Uniroyal probe device should be developed to the point that feasibility is demonstrated. Once the case for feasibility and marketability are made, it can be assumed that private industry will complete development.

2. Review the designs and field test the most promising existing techniques to determine what their minimum lifetime costs will be. For instance, it might be possible with today's electronics to code the output of battery powered tire mounted transmitters in such a way that a single point receiver (the distributed antenna systems that have been developed by TYRECHEK and others) could be used by increasing receiver gain and still have adequate rejection of spurious signals. A significant cost saving might be achieved in this manner and upon closer inspection there probably are other design changes that have the potential to substantially reduce costs.

   Another promising route to improving the cost projections for tire inflation sensors would be to demonstrate a reliability substantially better than that projected. This would involve testing the sensors over a long period of time - at least the life of one set of batteries and preferably longer. A number of sensors could be installed and left in service for extended intervals. The essential element of such a test program would be functional testing of the systems (by reducing tire pressure until an alarm is given) at periodic intervals. In this manner, reliability data, in the form of a mortality curve could be collected. It also would be desirable to collect data on the frequency of alarms given and the response rates achieved. However, this would not be absolutely necessary.

3. Better define consumer benefits through improved fuel economy and reduced tire wear. Although these benefits turned out to be quite small it is possible that with increased petroleum costs (which could conceivably double and triple fuel and tire costs over the next few years) that these costs could become a much bigger factor. Unfortunately, the data base for determining incidence and degree of underinflation are very scattered as is the sensitivity of tire wear to underinflation. A study

of these factors could provide the needed data base for future decisions.

3.2.3 Brake Light Intensity Sensor

3.2.3.1 Review of Justification

This sensor area was listed separately from the brake light electrical sensor in recognition of the possibility that there may be no electrical defect in the brake lights, yet the lights may not be visible because of obscurred lenses. Another failure mode - failure of the brake light switch - can be monitored electrically only by providing redundancy in the actuating switches -- one switch to light the lamps, a second to energize the sensor, which would then test for lamp function. With duplicate switches however, it might be more practical to eliminate faults by providing redundancy throughout the brake light system, rather than developing a sensor to detect the defects when they occur.

The conceptual difference between electrical and optical sensors was actually of significance in several of the Indiana cases. In the first of these, a vehicle with all rear lights functional was rear-ended under conditions of freezing rain. The stop lights were obscurred by the weather plus dirt on the lenses.

In a second case, a malfunction in the directional flasher rendered both the stop and brake lights inoperative (possibly) causing a rear-end collision.

3.2.3.2 Functional Requirements

In order to achieve the ranking cited, a brake light intensity sensor must sense the light output from outside the lens assembly. In the Indiana case involving the dirty lenses it is doubtful (in view of the weather conditions) that the driver would have corrected the difficulty even if the condition were indicated. To maximize the probability of owner response, it would be desirable to provide a go-no go indication rather than an analog indication of the light output available.

3.2.3.3 Candidate Techniques

No sensors meeting all of these requirements are currently available. Fiber optics light sensors have been occasionally used for light operation sensing in some high priced automobiles (Cadillac, Lincoln, etc.) for several years. For example, in the Cadillac, two light pipes, one for each brake light, extend from the light up over the rear window where they terminate in a single two element display located just over the center of the rear window. When the brakes are applied and the brake lights are operating normally, light is transmitted through the fiber optic light pipe and projected onto the back of a small tinted glass window (Figure 3-31). The operator can view the display in his rear view mirror and see if the lights are on or not. A fundamentally simple concept, it can inform the operator of any fault in the brake lighting system if he conscientiously observes the display periodically. If on the other hand he does not make the conscious effort to check the display the system is ineffective while those systems which produce a display when a fault is sensed are more likely to be observed by the non-attentive driver. The importance of this shortcoming is not known but would require evaluation before this concept could be highly recommended. Another problem with this concept is the poor readability of low cost systems (it has been observed that this type of display is almost completely washed out by sunlight). Low cost plastic light pipes typically have a light loss of approximately 50% per foot in the visible spectrum (See Figure 3-32) while glass light pipes have light losses of 10% per foot and better depending upon cost. The amount of light which passes through the optical interfaces collecting aperture to fiber optics, fiber optics to display panel, etc. is a function of care and attention, i.e., cost, applied to making the connection. A 50% light loss at each interface must be anticipated in this application. When it is further recognized that much less than 1% of the total light produced by a brake light can practically be collected for the display and that only some small fraction of that gets to the display panel then it is small wonder that readability is a problem. Readability can however be improved upon by increasing the light collecting aperture area, reducing interface losses, increasing the light pipe diameter, using better quality glass optical fibers, reducing the length of run from light to display and placing the display in an area with low ambient light. All of these options are either costly or inhibit the installation.

Finally, the installation cost for light pipes and displays is typically much higher than electrical wire because the light pipe takes an unusual path separate from any wiring. Thus, it is not bundled with others, it is placed in an unique location as is the display. Clearly the cost for light pipe systems can vary widely from one application to another.

Use of light sensitive devices such as silicon photodiodes is an obvious technique for light failure sensing. This technique makes it possible to overcome the readability problem inherent in fiber optics by energizing a typical display light with the signal from the photodiode. Unfortunately this concept requires a large number of separate system elements - photodiodes - operating off of reasonably well regulated power, power relays or SCR's to power the display, incandescent bulb, LED or other type of separately powered display, interconnecting wiring, etc. - forcing the concept to be expensive. There seems to be little potential for this concept except perhaps in some unusual applications.

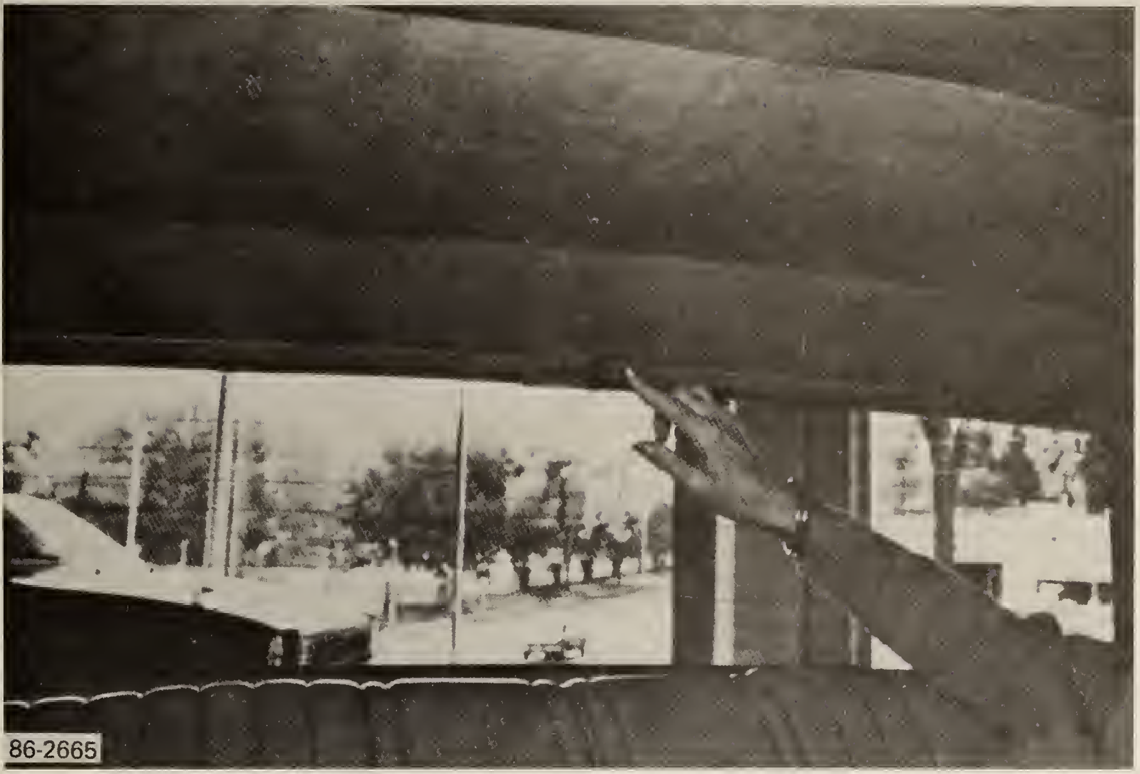


Figure 3–31 CADILLAC FIBER OPTIC DISPLAY

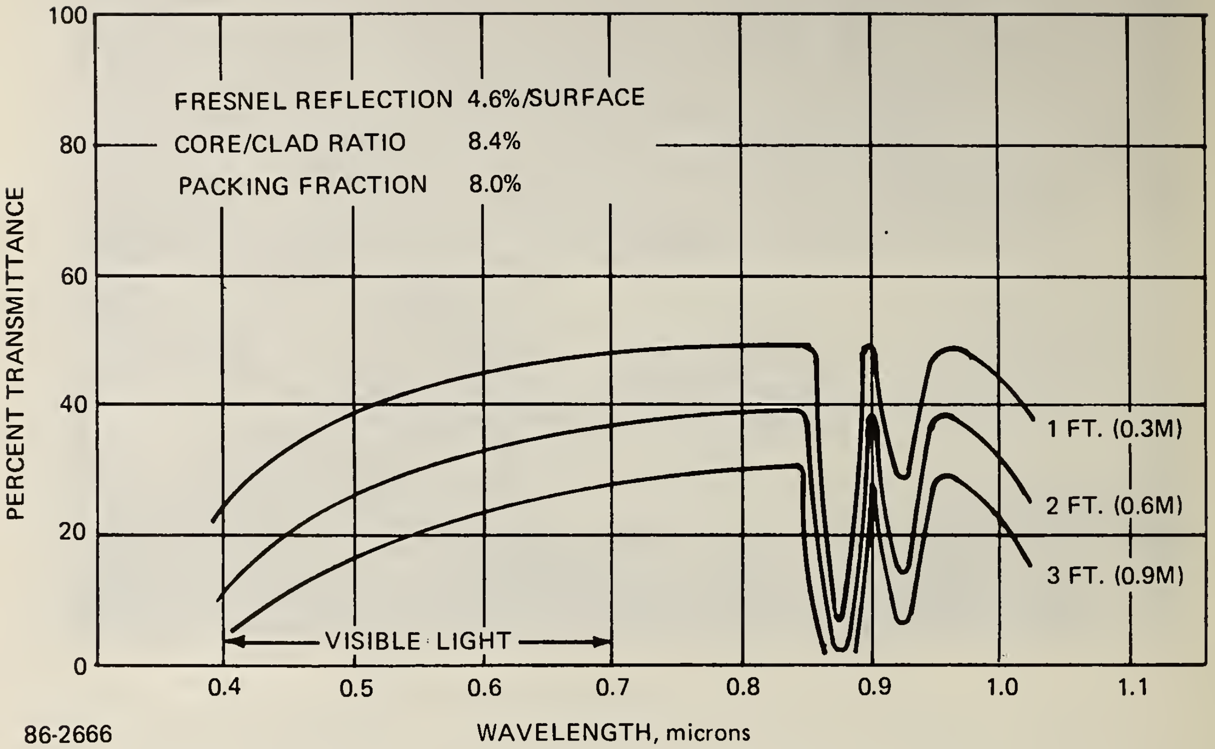


Figure 3–32 PLASTIC FIBER OPTIC TRANSMITTAL

3.2.3.4 System Tradeoffs

The fiber optics system for which costs have been developed assumes use of jacketed plastic fiber optic light pipe approximately 0.110 inch overall diameter with metal ferrule on back and for installation. Back lighted tinted glass plates in individual plastic mounting blocks will be displayed on each side inside the rear window (similar to systems that have been installed in Cadillacs and Lincolns).

Fiber optics - 6' @ $.15/ft x 2	=	$ 1.80
Displays - 2 @ $.50	=	1.00
OEM Cost	=	$ 2.80
Cost to Buyer (OEM x 4)	=	$11.20
50% Maintenance Allowance	=	5.60
Total Lifetime Cost	=	$16.80

Note that an OEM to consumer cost ratio of 4 has been used due to the higher than average installation cost.

3.2.3.5 Recommendations

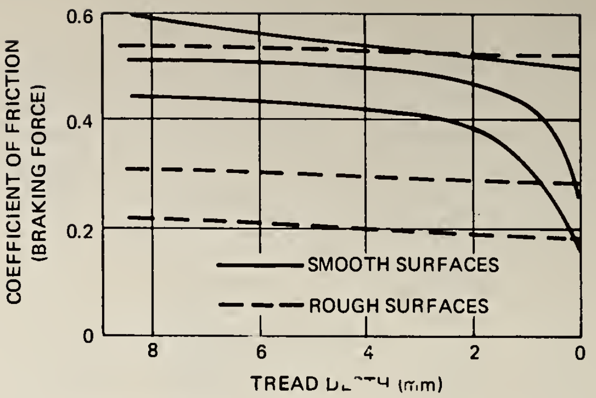
In view of the strong similarity between brake light optical and electrical sensors, a combined tradeoff and discussion are provided in Sections 3.2.6.4 and 3.2.6.5.

3.2.4 Tire Tread Depth Sensor

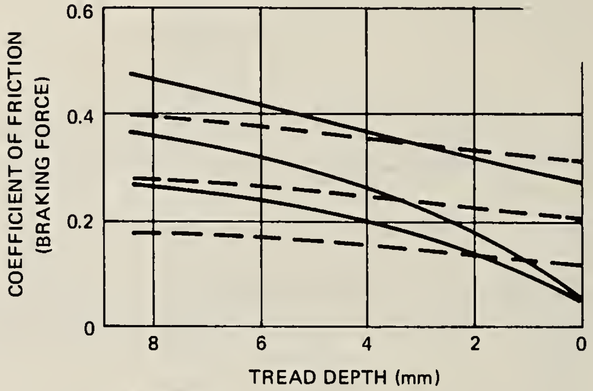
3.2.4.1 Review of Justification

Although tread depth is recognized as an important factor in wet-road cornering and braking, the best quantitative reference on the subject located by the authors is a figure by Sabey, which was reproduced without detailed comment in Reference 32. (See Figure 3-33.) With the exception of the low speed, rough road braking force characteristics, which displays a "Knee" at about 2/32" of tread depth, there appears to be nothing magic about this generally accepted inspection limit on tread depth. However, this limit appears to represent a minimum acceptable condition, with little allowance for further degradation.

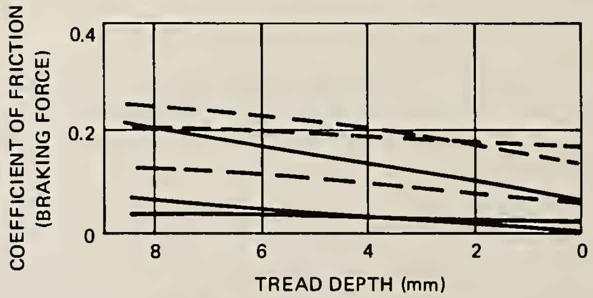
The Indiana data identified tire tread depth as the single most important cause of defect related accidents. However, tire tread depth was downgraded to third place as an area for sensor application because in about half the cases cited, the drivers stated that they were already aware of the condition of the tires.



(a) 30 mile/hr.



(b) 50 mile/hr.



(c) 80 mile/hr.

86-2667

Figure 3–33 EFFECT OF TREAD DEPTH ON WET ROAD SKIDDING RESISTANCE AT DIFFERENT SPEEDS (Ref. 32)

A further consideration in the use of the Indiana data is the fact that Indiana has an annual system of periodic motor vehicle inspection (PMVI) that includes tire tread examination.

Figure 3-34 shows distributions of accidents versus time and mileage since inspection for the Indiana sample. Since the incidence of accidents appears to follow a uniform distribution (the dotted line in each figure), the effect of inspection appears to be small. Whether this is due simply to an inadequate (too lenient) standard, or to a lack of rigor in applying the standard as written, cannot be determined from the available data.

3.2.4.2 Functional Requirements

Where does on-board sensing fit into this picture? Tread depth does not degrade at such a rate as to require real-time readout at the driver's seat. What seems to be called for is a method of alerting the driver and/or law enforcement personnel as to the condition of the tire tread. This method should be more forceful than the wear bars currently used as visual indicators.

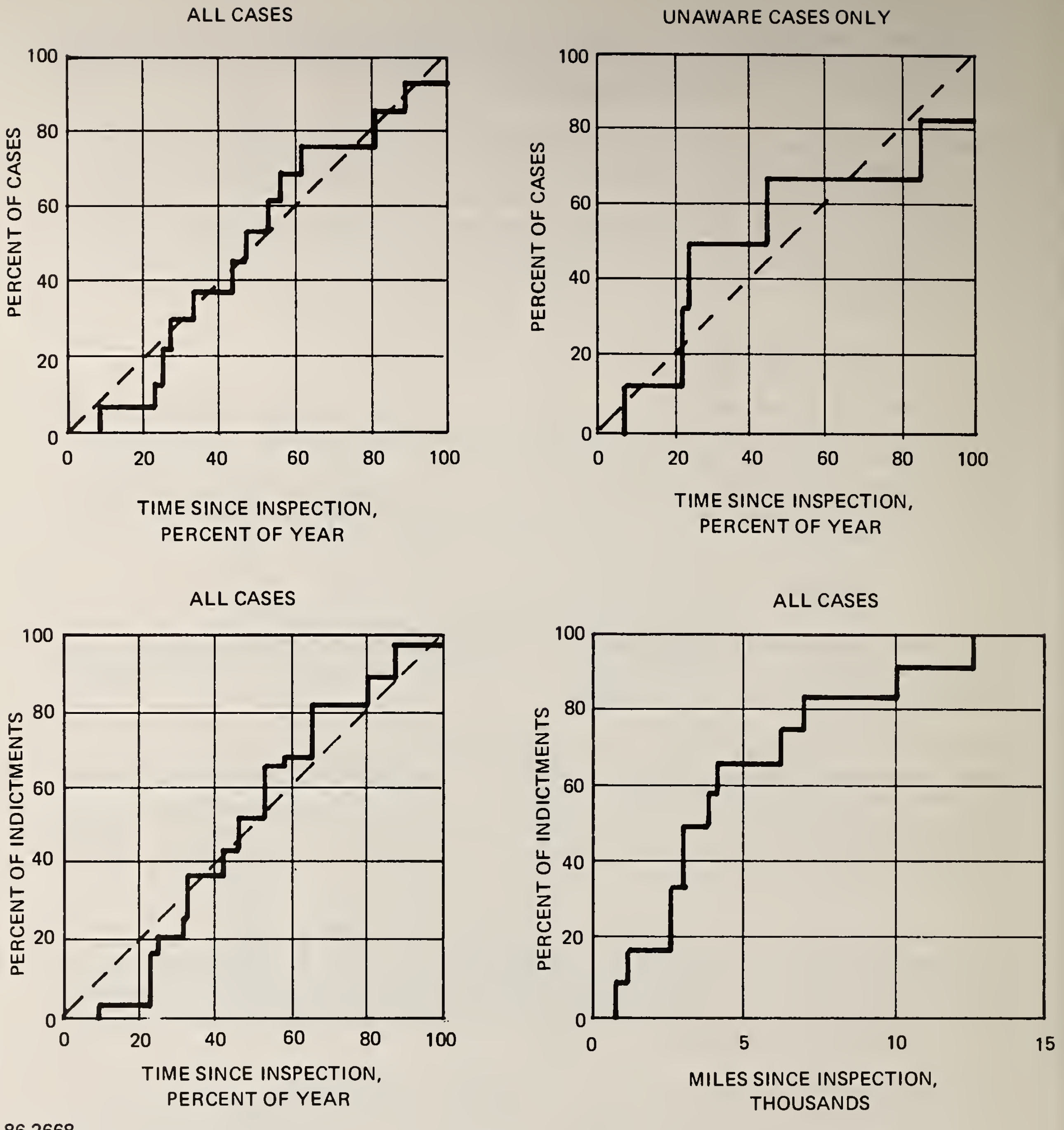
3.2.4.3 Candidate Techniques

All tires intended for highway use in the USA are required to have wear indicators molded into the tread. The intent is to speed up PMVI and to provide an indication to the owner.

Figure 3-35 indicates that, under certain conditions, existing tread wear indicators are not readily visible. Even when the tread condition is such that the need for replacement is evident, some motorists are not sufficiently attentive to notice it, as witnessed by the Indiana results. Although the effectiveness of currently available wear indicators is unknown, the cost of providing them is negligible.

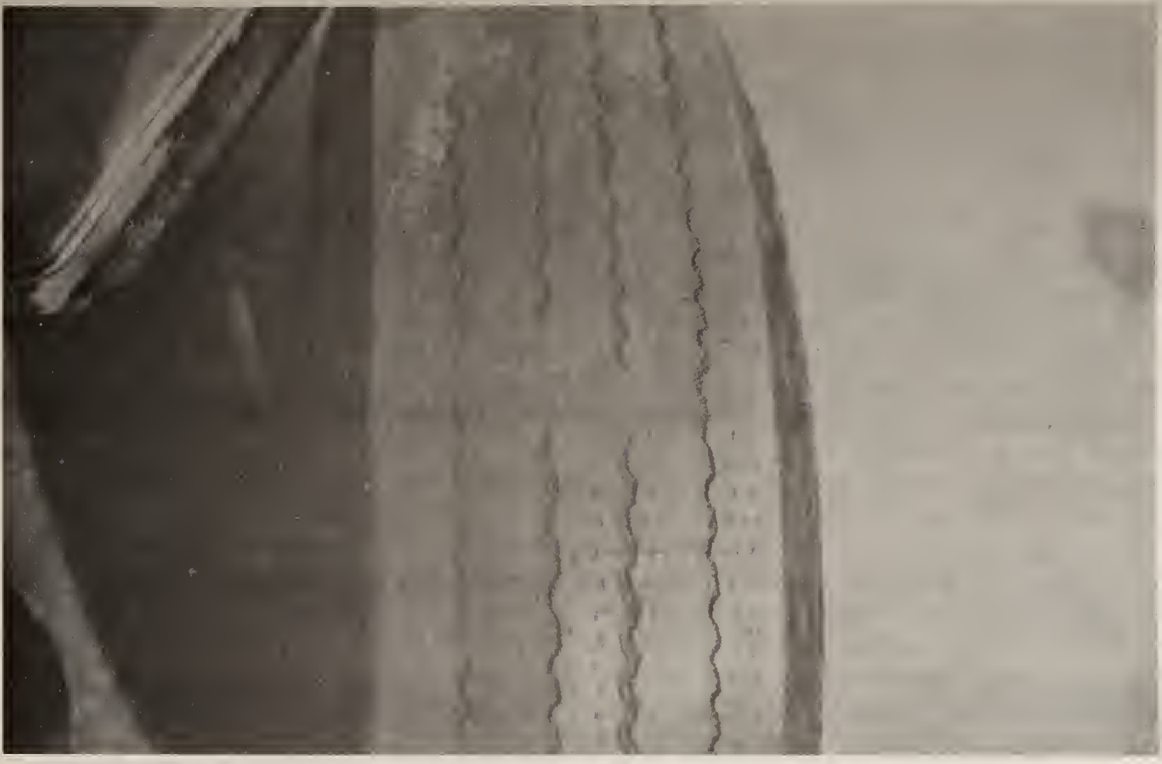
The visual indicators could be improved by providing an indicator of a contrasting color that would be exposed when the tread was worn below a specified level. However, Avco's dialog with tire industry representatives did not reveal a practical method for incorporating such a feature into the tire manufacturing process.

Another possibility would be design the tire tread so as to give an audible indication of wear below a certain point. Although this approach is not likely to have high effectiveness, it would represent a low (possibly zero) cost approach.

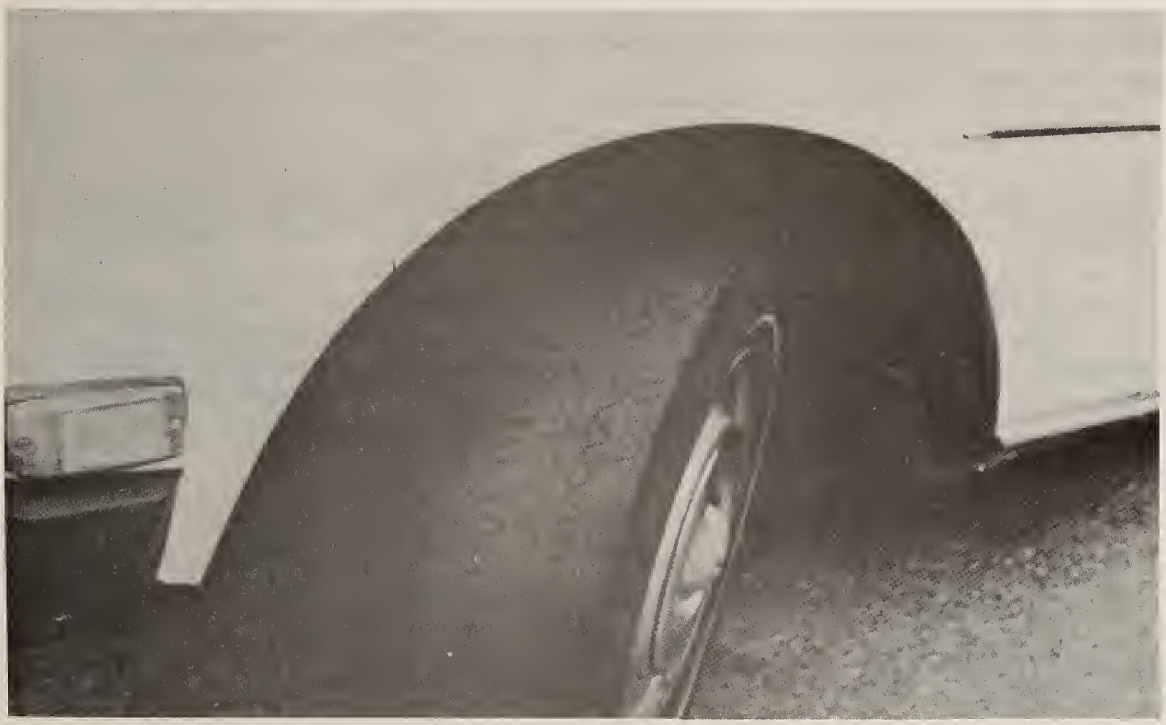


86-2668

Figure 3–34 RELATIONSHIP BETWEEN INDIANA INSPECTION AND ACCIDENTS INVOLVING TIRE TREAD DEPTH



THE TIRE IN THIS PHOTO DISPLAYS SLIGHTLY UNEVEN WEAR IN ADDITION TO ITS TREAD WEAR INDICATORS. ITS CONDITION IS APPARENT FROM A SUPERFICAL INSPECTION.



THE TIRE IN THIS PHOTO HAS WORN SO EVENLY THAT A SUPERFICAL INSPECTION MIGHT NOT BE SUFFICIENT TO DETECT ITS TRUE CONDITION.

86-2669

Figure 3–35 TREAD WEAR INDICATORS

3.2.4.4 Tradeoff Analysis

In Table 3-4, the (vehicle) lifetime cost of accidents due to inadequate tread depth is estimated to be \$45.56 for all accidents and \$22.78 for accidents in which the driver was unaware of the condition of his tires.

Since the cost of an improved indicator cannot now be estimated, a cost benefit analysis of the conventional type cannot be performed. Instead, let us calculate the break-even cost for such a device, to determine whether it is feasible to pursue the subject further. Using a (vehicle) lifetime tire consumption of 12 tires, the per-tire cost of accidents is \$3.80. This would be the break-even cost for an indicator with 100% effectiveness, i.e., one capable of eliminating tire tread accidents altogether. A more reasonable estimate is derived by assuming an effectiveness of 20% on those persons who would willfully ignore tire condition (50% of the Indiana sample) and an effectiveness of 50% on those remaining (who would be ignorant under the current scenario). Using these assumptions, the overall effectiveness of an improved wear indicator might be 35%. With this effectiveness, the break-even cost of an improved tread wear indicator would be \$1.33. This is a small, but not an insignificant number. However, this analysis neglects the increased cost to the motorist of more frequent tire replacement imposed by the stricter adherence to the wear standard. This might be significant if a substantial number of motorists currently use their tires beyond the rejection limit.

3.2.4.5 Recommendations

Further research is needed into the manufacturing problems associated with improved wear indicators. Additional research is also required into the existing tire replacement criteria of American motorists. This could be accomplished by examination of tires traded in. The reasons for the apparently low effectiveness of Indiana PMVI should also be determined. The effectiveness of alternative countermeasures such as public information campaigns, increased law enforcement, and increased frequency of PMVI should also be studied.

3.2.5 Steering Wheel Play Sensors

3.2.5.1 Review of Justification

Steering wheel play qualified for further consideration on the basis of the Indiana Investigations. Their finding that steering wheel freeplay can be a significant contributor to accidents is in qualitative agreement with the limit performance literature.

3.2.5.2 Functional Requirements

There is general agreement that steering wheel play is a gradually developing phenomenon, that should be adequately controlled through (annual) periodic inspection. In this regard, the performance of the Indiana inspection system is strongly suspect. Figures 36A and 36B show the cumulative distributions of observed system freeplay on the accident vehicles: the former on the basis of cases; the latter on the basis of the strength of the indictment. It can be seen that in many of these cases, the system freeplay greatly exceeds the inspection standard of 15 degrees. If the condition of the accident vehicles is estimated at its prior inspection, using the assumption that steering wheel freeplay for each vehicle is proportional to the cube of the odometer reading, most of the cases still exceed 20° freeplay (Table 3-20). The problem, therefore, appears to lie with the inspection process. An on-board sensor should be capable of performing inspection to the VIU standard of approximately 15 degrees.

TABLE 3–20. ESTIMATED STEERING PLAY AT INDIANA INSPECTION

			Mileage (thousands)		
Case no. (onsite)	Indictment	Play (degrees)	At time of accident	At last insp.	Play at insp. (est) (degrees)
3180	0.31	14	100.2	93.7	11
2197	0.60	21	unknown		unknown
3436	0.23	25	unknown		unknown
2353	0.15	26	105.5	104.7	25
3497	0.38	26	85.2	82.2	23
937	0.40	29	127.5	121.8	25
816	0.80	40	35.5	33.1	32
801	0.42	47	94.6	86.9	36
558	0.25	unknown			
2618	0.15	unknown			

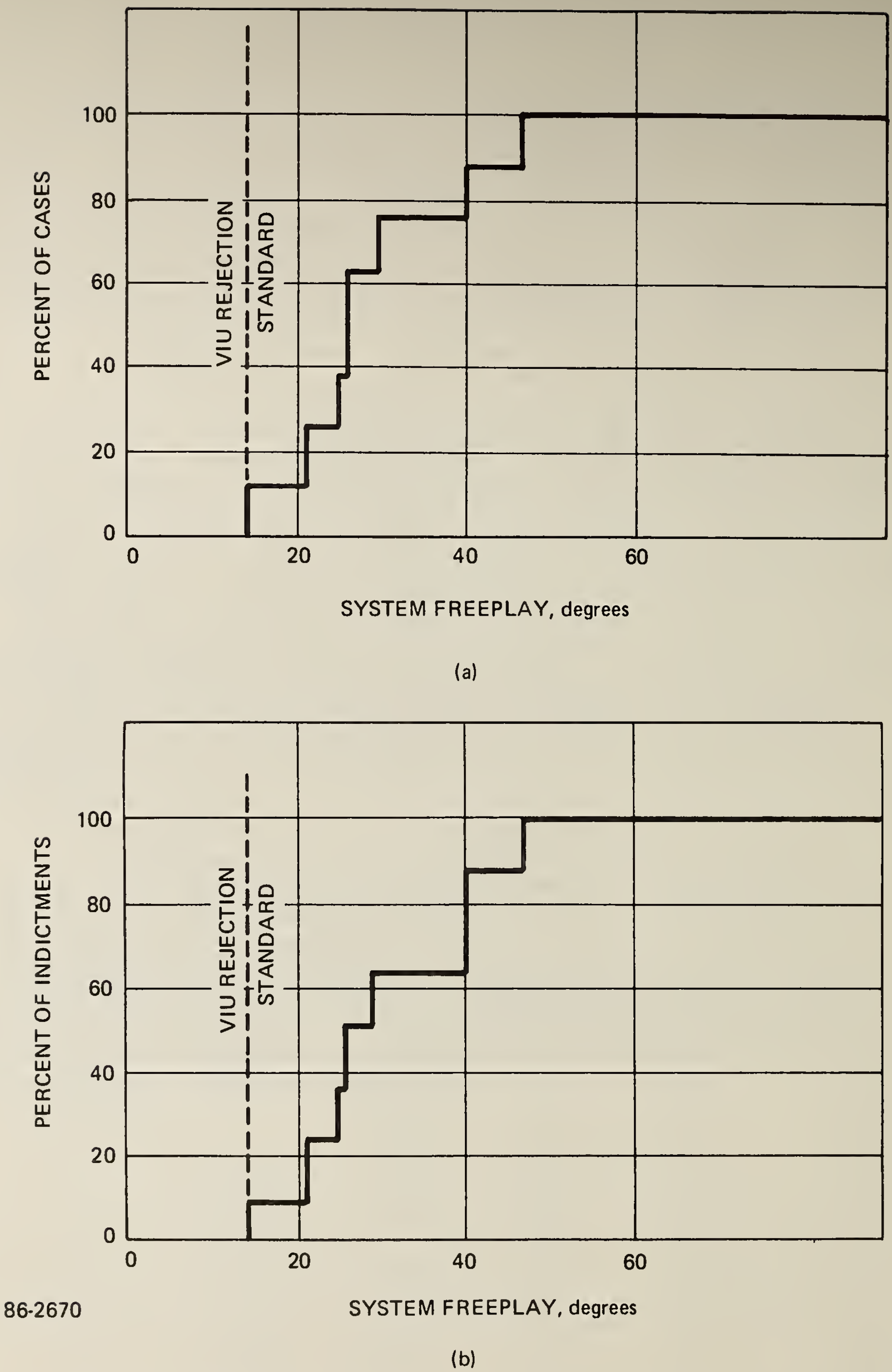


Figure 3–36 DISTRIBUTION OF STEERING WHEEL PLAY OBSERVED IN INDIANA ACCIDENT CASES

3.2.5.3 Candidate Techniques

There are no commercially available methods for providing an on-board measurement of steering system play. In theory at least, an indication of system play could be provided by installing potentiometers or similar rotary sensing devices at strategic points within the steering linkage. By moving the steering wheel back and forth, the resistance of the potentiometers could be traced out as shown in Figure 3-37.

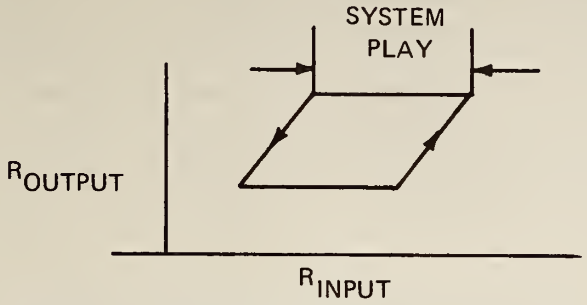


Figure 3–37 STEERING LINKAGE PLAY POTENTIOMETER INDICATIONS

The sensor outputs could then be processed through on-board logic set to energize an alarm when system play exceeded a predetermined maximum or the outputs could be carried to a central plug for off-board interpretation. Clearly the critical component in such a system would be the rotary sensors which would have to measure steering wheel rotation with a resolution of at least 3 degrees (to adequately support a 15 degree allowable lash) and measure front wheel rotation to an accuracy of at least 0.5 degrees (or an equivalent motion elsewhere in the steering linkage) if a reasonably accurate measurement is to be made. Resolution this fine is quite demanding and will drive the sensor cost up substantially. Probably of greater importance, it will mean that the sensors, mounting bracketry and any required linkage would have to remain tight and almost entirely free of backlash throughout the life of the automobile - this would appear to present a formidable problem for a necessarily very low cost sensor.

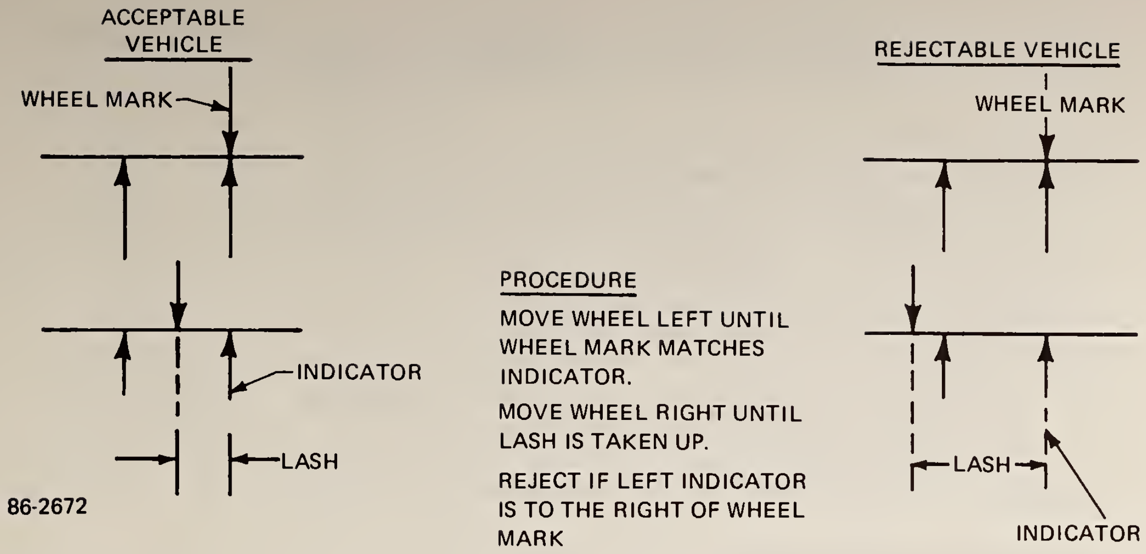
There are various devices for sensing rotation of one element with respect to another: potentiometers, in widespread use in electronics for adjusting or trimming resistance values, and in automobiles for regulating electric motor speeds; variable capacitors or inductors as are used for tuning radios, televisions, etc.; microsyns or optical encoders for precise measurement of inertial instrument position, etc. When these devices are reviewed for application to measurement of steering wheel play the conclusions are quite discouraging. The first problem is that many of the possibilities, such as optical encoders and microsyns are, because of their inherent complexity, too costly for this application (it is difficult to imagine that even the simplest device manufactured in quantities of millions could cost less than several dollars each) although they are non-contacting devices that might well be expected to operate without maintenance throughout the entire automobile lifetime. The other alternatives, such as potentiometers and variable capacitors (or inductors) can be made very inexpensively (pennies per unit) for uses that require a few hundred or thousand operating cycles but they are contacting devices which are subject to wear and are sensitive to contamination. (The environment near the front wheels will be very dirty.) To provide any of these devices with adequate cycle lives (certainly millions of movements such a device would experience during 100,000 miles of automobile operation) will almost certainly result in unacceptably high costs -- over $1 per sensor. It is doubtful that any sensor exists in a form directly usable in this application. Thus a development program, with extensive testing, would be required before the sensor costs could be accurately established.

An alternative, simpler method would be to provide a pair of reference marks on the steering column and a reference mark on a stationary object (or vice-versa) that would provide a visual indication of excessive play. (Figure 3-38) This technique would obviously be to support and hopefully improve upon the accuracy of manual inspection and would not provide an automatic display to the operator that steering wheel play exceeded allowable tolerances. It is something that could be implemented very inexpensively (estimated at less than 50 cents on the retail cost of an automobile) which could enhance the ability of the inspector to make a quantitative (thus potentially more accurate) measurement, and by its presence perhaps make it more likely that the inspection is performed.

3.2.5.4 System Tradeoffs

Cost estimates for three systems - two electrical (with and without on-board display), and a visual indicator are provided in Table 3-21.

It is clear that the cost for a system with on-board display is prohibitively high. The on-board electronics has been assumed to be that which is required to provide regulated power to potentiometers, to make a simple voltage comparison and to drive a dashboard light display when the difference voltage exceeds some allowable reference while the sensors are assumed to be simple low cost wire-wound potentiometers. This produces the minimum cost but it should be recognized that the estimate is probably low. If non-contacting sensors are used, not only will the sensor costs increase but the electronics cost will probably increase substantially.



PROCEDURE

MOVE WHEEL LEFT UNTIL WHEEL MARK MATCHES INDICATOR.

MOVE WHEEL RIGHT UNTIL LASH IS TAKEN UP.

REJECT IF LEFT INDICATOR IS TO THE RIGHT OF WHEEL MARK

Figure 3–38 INSPECTION OF STEERING PLAY USING REFERENCE MARKS

On-board sensors with off-board read out make much more sense as the cost is lower and the system supports periodic inspection which is where steering wheel play should logically be measured and limits enforced. No cost has been included for off-board logic on the assumption that future inspection facilities will have equipment to support this relatively simple diagnosis. Special test sets for this purpose could probably be procured for about $100.

Against an estimated cost of accidents caused by steering wheel play of $10, (Table 3-4) the cost of an electrical system with off-board readout is too high at $18. The cost of annual steering inspection, exclusive of the compliance cost (discounted cost to repair) is estimated at $.50/year or $6.00 per vehicle life (Ref. 26).

3.2.5.5 Recommendations

The addition of the visual indicator, with a lifetime cost of $1.50, would be cost-effective if it permitted a 25% savings in inspection cost, (without raising effectiveness) or a 6% increase in inspection effectiveness with no change in cost. While the former is unlikely, the latter is a distinct possibility.

TABLE 3–21. COSTS OF STEERING PLAY SENSORS

Option 1 - Active sensors with on-board display

Option 2 - Active sensors with off-board readout

Option 3 - Visual indicators

Cost element	Option 1	Option 2	Option 3
3 Rotary sensors	$ 3.00	$ 3.00	-
Interconnecting wiring	1.50	1.50	-
On-board electronics	4.00	-	-
On-board display	1.00	-	-
Central plug	-	.50	-
Visual indicator	-	-	$ .50
Total OEM Cost	$ 9.50	$ 5.00	$ .50
Retail Cost (OEM x 3)	$28.50	$15.00	$1.50
Maintenance Cost (OEM x 20%)	$ 5.70	$ 3.00	-
Total User Cost	$34.20	$18.00	$1.50

3.2.6 Brake Light Electrical Sensor*

3.2.6.1 Review of Justification

The brake light electrical sensor was included on the basis of its frequency of occurrence in the Indiana Level C cases. Accidents in which brake light defects are cited as causal factors tend to be rear-end collisions in which the impacted vehicle is stationary. The assessment of brake light defect causation is based on the investigator's judgment as to whether the striking vehicle would have stopped in time, were the brake lights working. This is a more subjective process than, say, determining whether a brake defect is causative, since in the latter case, physical evidence is available on the dynamics of the vehicles involved. A further complication is posed by the difficulty of determining whether a brake light defect was accident induced.

The numerical indictments of brake light defects averaged about 50%. It might be possible to obtain an analytical check of this result by comparing the observed frequency of brake light defects in the at-large population and the at-large frequency of rear-end collisions with the corresponding frequencies in the Indiana Level C area. That is, if brake light defects are found in 50% of all rear-end collisions and in only 2% of the at-large population, the case for a cause and affect relationship would be strengthened. On the other hand, if brake light defects are found in approximately the same fraction of rear end collisions as in the at-large population, an opposite inference would be drawn.

3.2.6.2 Functional Requirements

The requirement for a brake light sensor is to indicate a failure whenever the brakes are applied and the brake light circuit is not drawing the proper amount of current.

3.2.6.3 Candidate Techniques

There are some available techniques for electrically detecting failure of lights in automobile circuits that can be considered for monitoring brake light operation. All utilize the same basic phenomena -- absence of current in the power lines to the lights when a failure interrupts the circuit. On-board light failure detection systems have been installed on some automobiles in recent years, including various models of Toyota and Honda. Most have used reed relays or dropping resistor circuits for sensing although other techniques such as diode drop circuits or Hall Effect devices could be used.

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*See Section 3.2.3 Brake Light Intensity Sensor.

Figure 3-39 depicts a typical reed relay sensing system while Figure 3-40 shows one circuitry configuration for a diode drop sensing system.* Current passing through the reed relay coil produces a magnetic field to open the normally closed reed relay contacts thereby opening the display lamp drive circuit. Failure in either stop light circuit will cause the reed contacts to close and energize the display lamp when the stop light switch is on. The diode drop circuit utilizes the forward bias voltage drop of a diode to drive a transistor in the display lamp circuit. When the brake light switch is on and the diode drop is normal the display light is not energized but when the brake light switch is on and no diode drop exists, indicating no current flowing in the brake light circuit, the display lamp is energized. The dropping resistor circuit operates in much the same manner as the diode drop circuit except that the diode drop circuit will produce a constant insertion loss of approximately 0.7 volt while the resistor insertion loss will be a function of many variables including resistor size, lamp resistance, operating voltage, and temperature.

It is clear that the reed relay, diode drop or dropping resistor circuits can all be considered practical brake light failure detection concepts for they are all quite capable of sensing light circuit failures and reliably producing an alarm through all operating environments. Insofar as their effect on normal operation of the light circuit is concerned there is little to be concerned with. The probability that they will cause failure of the system is remote for the elements that are in the lighting circuit, coils, resistors or diodes are, when properly designed, all highly reliable and should degrade overall system reliability a negligible amount. Insertion losses are also quite small, normally less than 1 volt in all cases, and should create no problems with lighting system design.

The most significant deciding factor among them will probably turn out to be cost. All are relatively low cost with no overriding advantage for any one system. It would appear however that the ability to manufacture diode drop and dropping resistor circuits with hybrid technology could give them a cost advantage over the reed switch concept, particularly if the detection circuit is extended to other lights on the automobile.

It would be wise in any light failure detection circuit to incorporate other capabilities to increase system effectiveness. For example there should be a self test feature which energizes the display light when the ignition switch is turned on so the operator can know that the system is functional. The display should also be energized when a blown fuze or circuit breaker causes a system outage. It also seems

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*This is an Avco proposed circuit and is incorporated in an active display provided under this contract. (See Figure 4–3.)

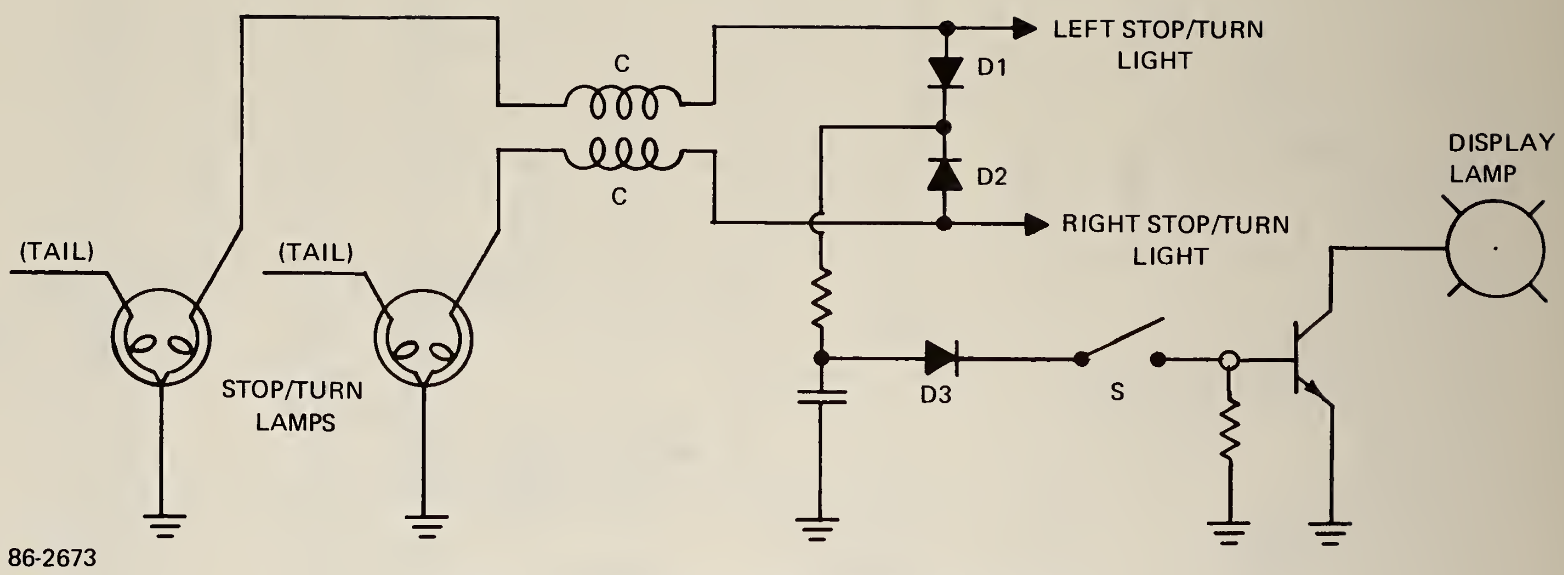
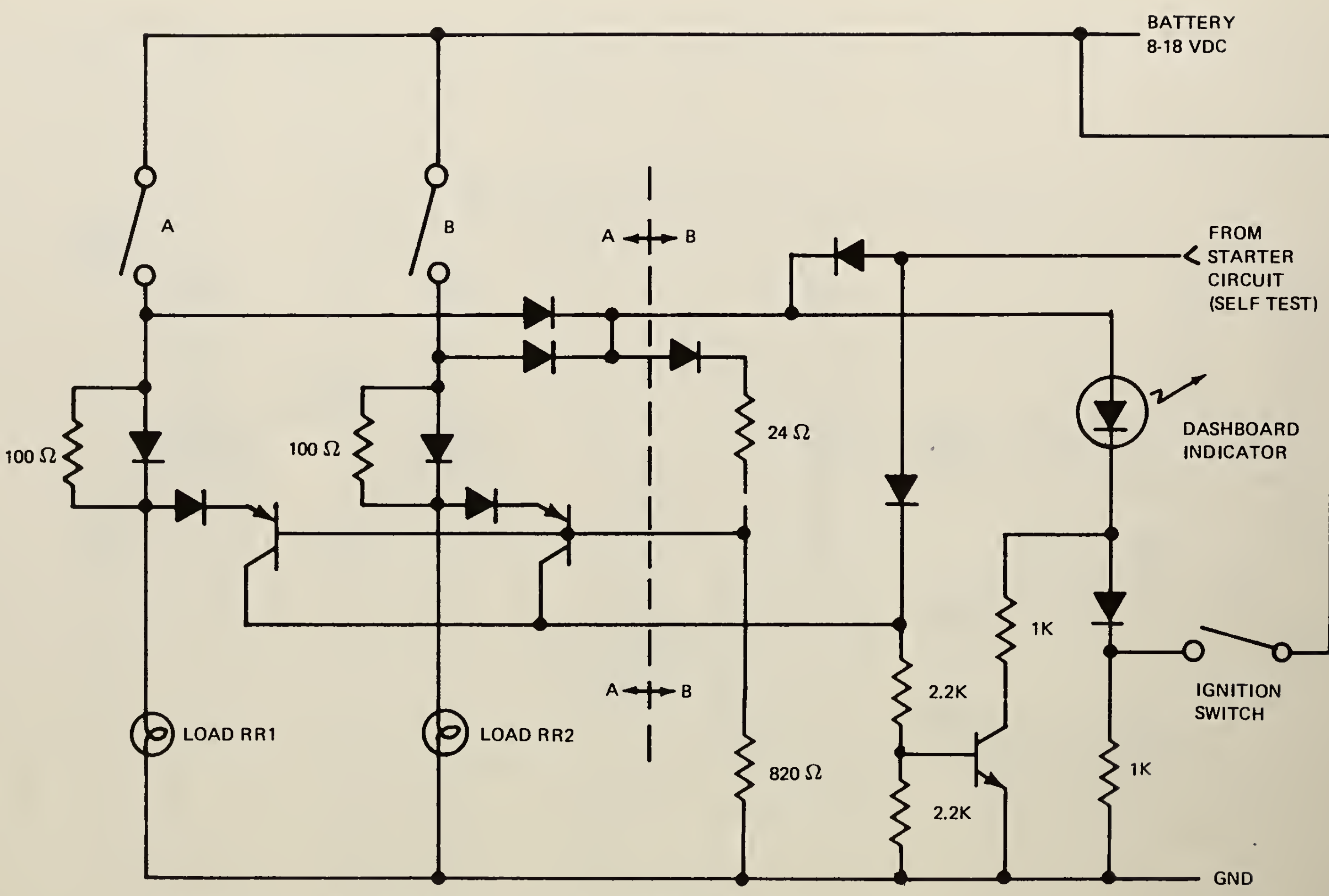


Figure 3–39 BRAKE LIGHT SENSOR USING REED RELAY



SIDE A CIRCUITS ARE DUPLICATED FOR EACH ADDITIONAL LOAD.

SIDE B CIRCUIT IS DUPLICATED FOR EACH GROUP OF LOADS TO BE MONITORED.

86-2674

Figure 3—40 BRAKE LIGHT SENSOR USING DIODE VOLTAGE DROPS

advisable to have a brake light failure detection system that detects failure of the brake light switch which is actuated by brake pedal motion or hydraulic line pressure. Another (redundant) switch would have to be installed to incorporate this feature but it is expected that an analysis of brake light failure causes would point out that the brake light switch is a significant failure cause. Furthermore failure of this switch causes all brake lights to fail, whereas other single failure mechanisms will generally leave one or more brake lights in operation. In task 4.0 Avco designed and built a model brake light failure sensing system incorporating these features. This is illustrated in Figures 3-40 and 4-3.

In conclusion, it is clear that no new hardware development is required and that brake light detection systems can be implemented at any time. Table 3-22 outlines a typical brake light failure detection system specification.

TABLE 3–22. SPECIFICATION – BRAKE LIGHT FAILURE DETECTION SYSTEM

1. Operating voltage: 10-16V d-c at battery.
2. Operating temperature range -

Hood	Car	Trunk
-20 to 250° F	-20 to 180° F	-20 to 260° F

3. Storage temperature: -40° F min to 260° F max.
4. Insertion loss: 0.5V drop desired with a max of 1.0 vdc.
5. Series sense element: must remain in calibration after sustaining a short circuit condition for a period of 5 s.
6. Indicator lamp: must be tested at each engine start, and preferably connected directly to battery.
7. Detection system: must remain in operating condition when subjected to the transients normally encountered in automotive electrical circuits.
8. Indicates blown fuze.
9. Indicates failed brake light switch.

Note: The Avco proposed system, shown in Figure 3-40 and provided as an operational display as described in Section 4.0 incorporates all the above requirements.

Another method of indicating lamp failures is commonly used for directional signals. The flashing device, being load-sensitive, will either fail to flash, or operate at a markedly different rate. Whenever brake lights are combined with turn signals, this technique also monitors brake light function. However a fault indication can be caused by either an inoperative front turning light (parking light) or a rear turning light (stop light). To find out which, the driver must inspect the outside of the car with the turning signals on. Further, there is usually no indication in the operator's manual or on the instrument panel as to the significance of the steady glow of the turning light signal indicator. Unless the driver knows about this, or asks a mechanic why turning signal indicator is misbehaving, he will never know that one of his stop lights may be out.

3.2.6.4 System Tradeoffs

As mentioned in Section 3.2.3, this section will discuss both electrical and optical sensors for brake light operation. However, the first order of business is the development of a cost estimate for an electrical brake light sensor. The system costed monitors the operation of two brake lights only. It detects failure of the brake pedal switch plus fuzes/circuit breakers and senses presence of current (OK) or lack of current (NG) in the lighting circuit when a separate brake switch is closed. Failure of either brake light will cause a single failure indicator to light up.

Cost Element	
Display	$ 1.00
Wire (2 ft. @ $.01)	.02
Brake Switch (Redundant)	.50
Connectors (4 @ $.10)	.40
Hybrid Detector Circuit	1.50
OEM Component Cost	$ 3.42
User Cost (OEM x 3)	$10.26
Maintenance Allowance (50%)	5.13
Lifetime Cost to User	$15.39

Comparison of Electrical vs. Optical Brake Light Failure Indicators

There are many techniques available for detecting failures in lighting circuits that have been developed for automobiles and others that could be considered. The choice to be made is largely one of performance capability vs. cost. The various concepts, four of them are blocked out in Figure 3-41, can be broken into two broad categories - optical or electrical.

Optical techniques that might be considered include both fiber optics and light sensing devices (optical diodes). Optical devices have the advantage of providing an end-to-end measurement in that they look at the final consequence of closing the brake light switch by depressing the brake pedal. Thus they are able to detect certain failure modes (such as a shunt path for brake light power which might cause the light to be unacceptably dim yet an electrical sensor might be insensitive to the condition), that might not be detected by electrical sensors. The fact that optical sensors must be placed in or on the light itself means that long and costly sensing lines, fiber optics or electrical wire, are required to bring the signal into the operators view. Electrical brake light failure sensors, on the other hand, can usually be placed in the circuit under the dashboard where wire runs to a panel display are very short. This creates a significant cost advantage for the electrical detection system.

The performance comparisons between systems are highlighted in Table 3-23. The advanced electrical sensor, costed at $15.00, has all the capability of the simple fiber optic sensor (costed at $16.80) and a vastly superior display. Improved display capability can be achieved with the optical sensors only at greatly increased cost (light sensing diode system).

TABLE 3–23. PERFORMANCE COMPARISONS BRAKE LIGHT SENSORS

Detector concept	Failed light bulb	Misc. electrical faults	Blown fuze	Faulty brake pedal switch	Display capability
Fiber Optic	Yes	Yes	Yes	Yes	poor to fair
Light sensor/ alarm	Yes	Almost always	No	No	excellent
Basic current sensor/alarm	Yes	Sometimes	No	No	excellent
Advanced current sensor/alarm	Yes	Yes	Yes	Yes	excellent

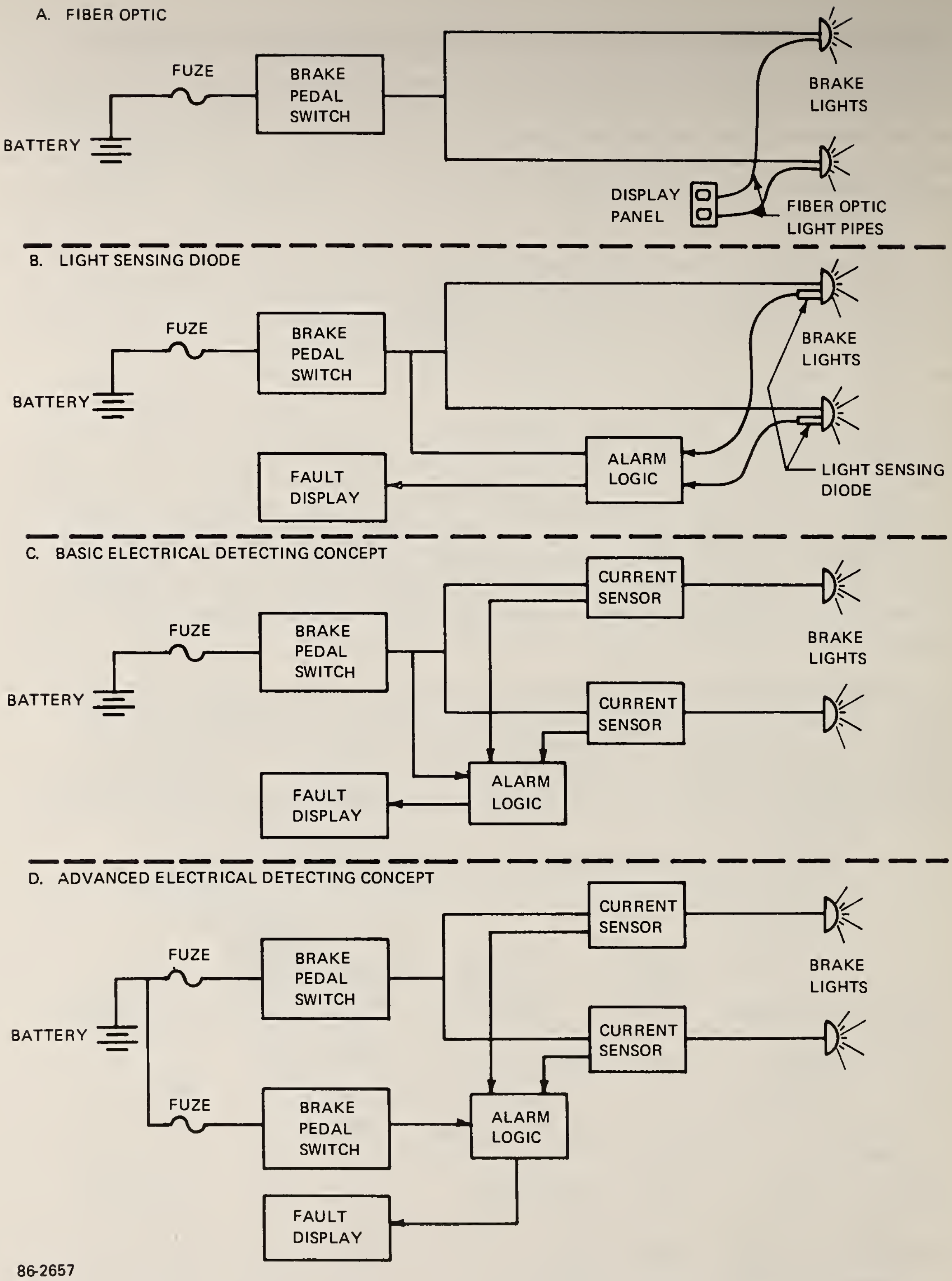


Figure 3—41 BRAKE LIGHT FAILURE SENSING CONCEPTS

On the other hand, cost reductions in the electrical sensor are possible by eliminating the redundant actuating switch, providing more detailed analysis shows switch failures to be a sufficiently small contributor to the problem.

The comparison of sensor costs and benefits may be somewhat misleading, since the baseline estimate of accident benefit from Table 3-10 is only $4.84. Table 3-3 indicates that the safety criticality of brake lights is highly uncertain, with estimates differing by almost a factor of 10. The lifetime safety benefit number from Table 3-5 ($29.44) shows brake light sensors more favorably.

3.2.6.5 Recommendations

On the basis of large uncertainties in the benefit estimates, sensors for brake lights are judged to be potentially cost beneficial. However, a final determination cannot be made until the safety criticality of brake light failures becomes more clearly defined.

3.2.7 Friction Material Wear Sensors

3.2.7.1 Review of Justification

One point of view on the relationship between thin pads or linings and brake system performance is represented in two experimental studies conducted by Bendix Research Labs (Refs. 9 and 10). In the 1972 study (Ref. 9) the effect of thin linings was evaluated by dynamometer testing of thinned linings. Subsequently, computer computation was used to determine stopping distance. In the 1974 study, (Ref. 10) these studies were extended by including several aftermarket pads and linings and the computer simulations were dropped.

The conclusions of the studies are quoted in Table 3-24. In the first study, the only performance difference noted was in the fade resistance of thinned disc pads. In the second study, even this property was determined to be non-characteristic, and it was concluded that: "performance tests, such as effectiveness or fade, are not useful in detecting the presence of thin friction materials in a brake system."

Conclusions above notwithstanding, brake friction material wear was frequently cited as a causative factor in the Indiana studies. Superficially, at least, this represents a contradiction; one whose resolution necessitates a closer look at both studies.

The Indiana indictments of friction material wear have been made only in cases where linings/pads have been worn to a condition of metal-to-metal contact, and where physical evidence of brake malperformance could

TABLE 3–24. FINDINGS OF BENDIX STUDIES ON PERFORMANCE OF BRAKES WITH THIN FRICTION MATERIALS

Type of system	Performance characteristics	1972 (Ref. 9)	1974 (Ref. 10)
Disc	Fade Resistance	"marked decrease ... below .100 inch."	"Thin or worn materials do not consistently or greatly affect brake effectiveness or fade performance."
	Effectiveness	"None of the degradation modes produced significantly large deteriorations"	
Drum	Fade Resistance	"No marked reduction in fade properties"	
	Effectiveness	"None of the degradation modes produced significantly large deteriorations"	

also be demonstrated. Indictments have been concentrated on drum brake systems, whose performance sensitivity to friction coefficient is corroborated in the first Bendix report*, (Figure 3-42A). The theoretical case against metal-to-metal contact as a source of brake performance problems then rests on variations in friction properties arising from differences in surface condition, and/or temperature. The question of whether these variations are manifest at normal levels of effort, as opposed to the crisis immediately preceding the accident, is best answered using Indiana's own data. Of nine cases where metal-to-metal contact was cited, four drivers indicated (in post-crash interviews) an awareness of abnormal brake function prior to the accident. In another case, a strong pull was noted by IRPS personnel in a post-crash test drive. In still another case, low braking effort was noted when the vehicle was tested on a high speed Clayton brake tester. This makes a total of six of nine cases in which the causal factor was apparently detected (or detectable) prior to the accident.

In summary, the Indiana indictments of thin linings appear to be based on plausible reasoning, and are supported by substantive evidence that some conditions of metal-to-metal contact do have detectable consequences.

Re-examination of the Bendix studies provides additional evidence that the apparent contradiction may be illusory. Testing of brakes with actual metal-to-metal contact represented only a subset of the tests performed. The first test involved a set of disc brake pads and a set of linings with no friction material whatsoever. In this instance, the disc and pads seized during pre-test burnishing, and sheared off the wheel studs. The drum brakes also exhibited a large torque impulse, and damaged the backing plate. Force testing was not completed. In a second attempt, a set of drum brake linings was thinned until bare metal was exposed at the center of the shoe. This set of linings was successfully tested and contributed to the conclusions cited in Table 3-24. In several other instances, metal-to-metal contact developed in the course of testing thinned disc pads. This condition was not always cited in the test results, but was evident in photographs of the test specimens.

Evidence that other factors can affect drum brake performance is also obtainable from the Bendix reports. Figure 3-43 shows the effect of lining contact points on the effectiveness of drum brakes. Similar results can be expected for varying the coefficient of friction (via exposed metal at the ends) circumferentially around the shoe. It is sometimes observed that certain drum brakes have an input-output characteristic that is concave upward, developing more than proportionally increasing torque with increasing line pressure. Brakes with this characteristic are difficult to modulate at high force levels, because a small input force change produces a large response, and may cause a wheel to lock. Most of the test curves shown in the Bendix reports are

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*Figure 3—42B indicates that disc brakes are less sensitive to friction changes.

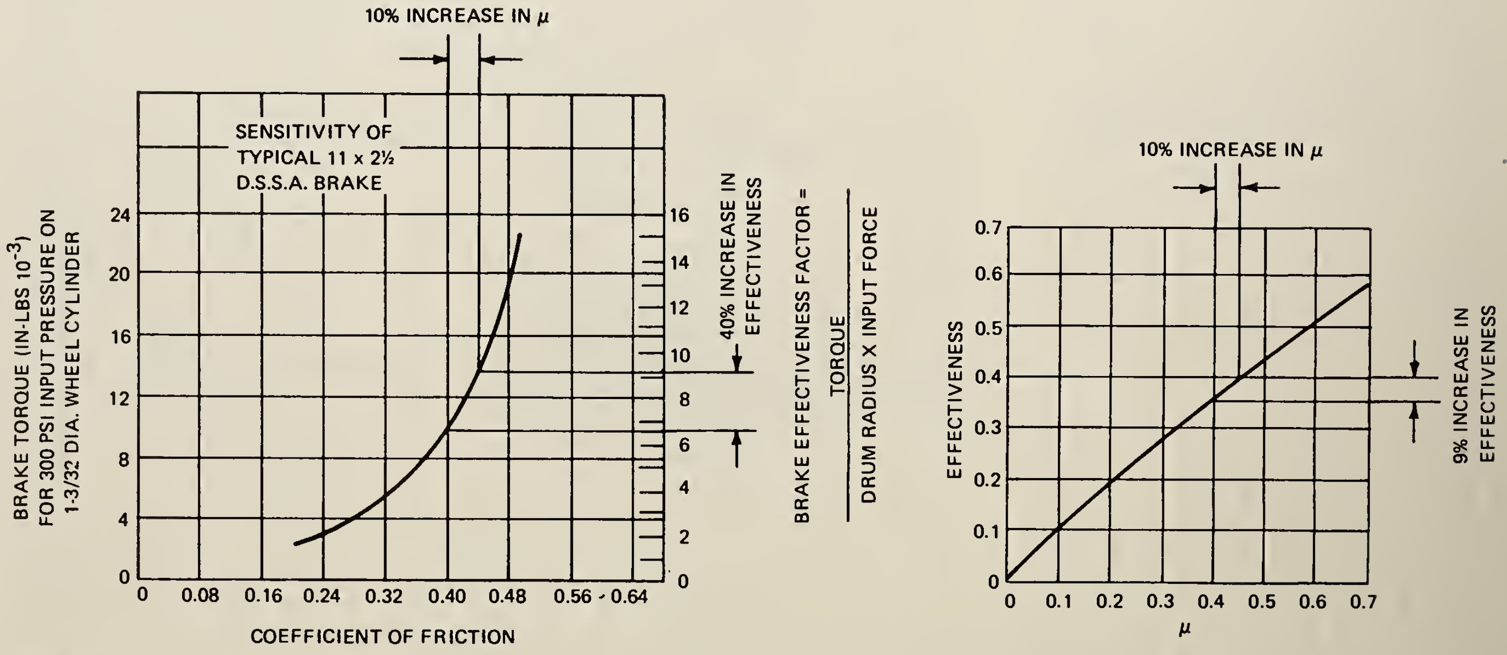

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Figure 3—42 BRAKE SENSITIVITY TO FRICTION COEFFICIENT (Ref. 9)

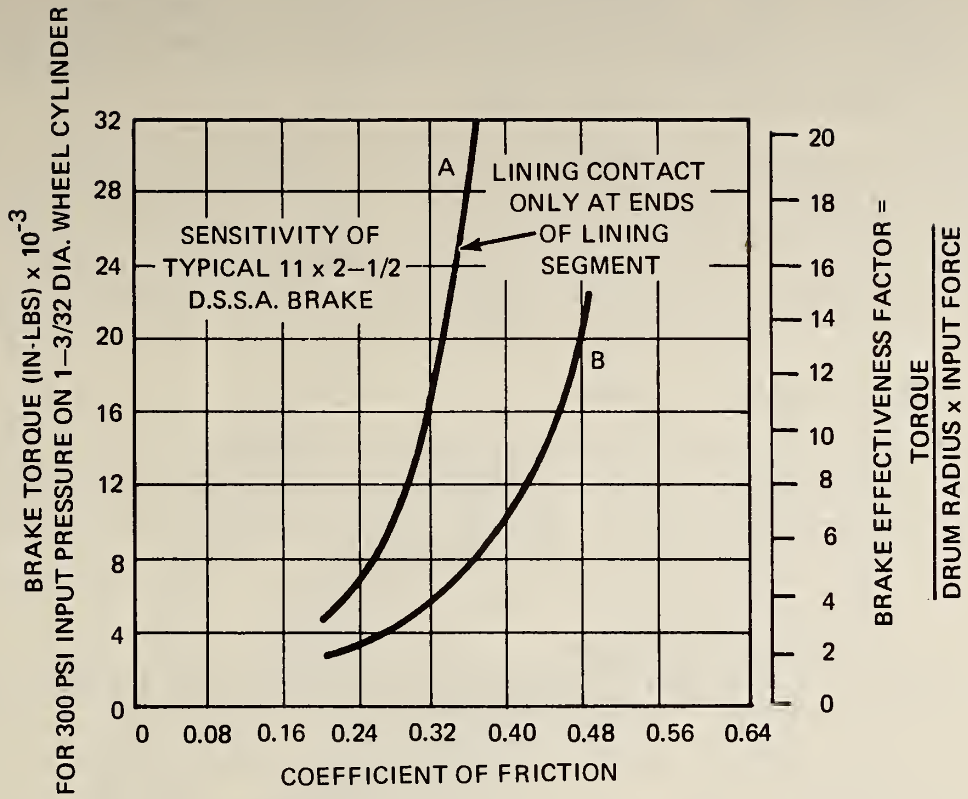

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Figure 3–43 EFFECT OF LINING CONTACT ON DRUM BRAKE EFFECTIVENESS (Ref. 9)

quite linear, indicating that testing was performed on a well-designed brake. However, the problem can arise due to other conditions, as indicated in Figure 3-44. The source of this effect is compliance in the shoe or drum, which causes the ends of the shoe to "dig-in" at high force levels. The problem can be exacerbated by faulty design of the brake to begin with, or by worn drums.

In summary, only one test result is quoted by Bendix for metal-to-metal contact in drum brakes; the test involved a set of linings thinned at the least critical place - in the center. Although this test gives negative results there is ample evidence elsewhere in the report to support the notion that metal-to-metal contact is an important potential cause of abnormal drum brake performance.

3.2.7.2 Functional Requirements

Granting the premise that metal-to-metal contact is the only area of concern, the warning threshold should be set as close to this condition as practical, allowing only a reasonable response time from the motorist and for uneven wear over the friction surface.

3.2.7.3 Candidate Techniques

The following types of sensors have been considered and, in many cases, reduced to practice:

- Electrical
- Acoustic
- Mechanical
- Smoke/Smell
- Visual Indicators
- Tactile (Pedal Feel) Indicators

Table 3-25 lists some of the models and manufacturers currently providing wear sensors. The following discussions which are based on Ref. 33, describe production versions, and concepts of the various sensor categories. The discussions cover the state-of-the-art but do not claim to be all inclusive due to the very large number of difference concepts that have been generated by the industry. Although nearly all of these are applied to disc brake pads only, the basic principles of application for drum brake linings are identical.

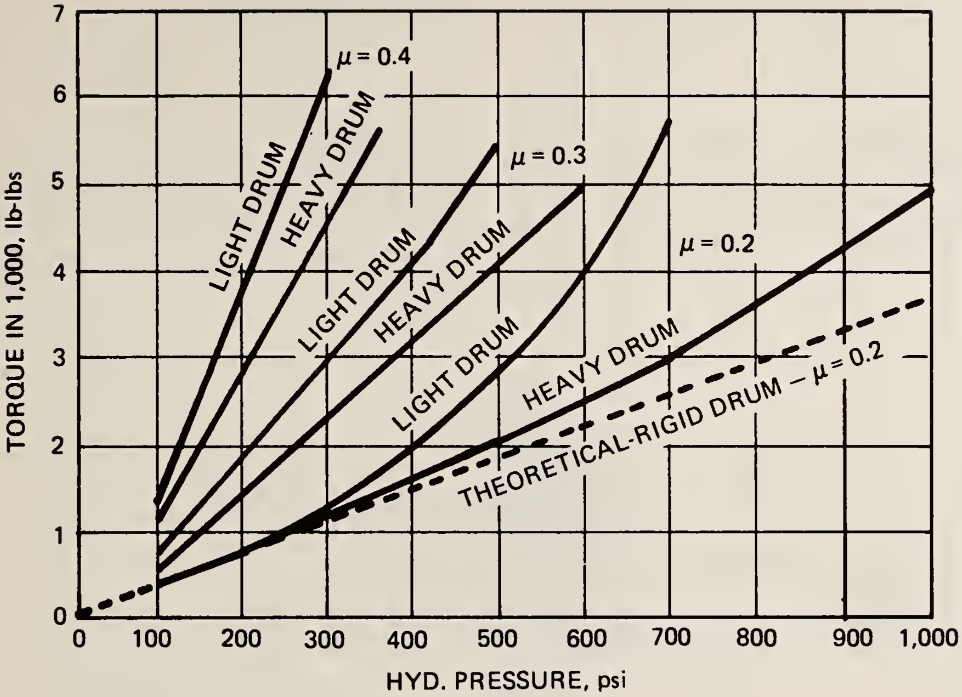

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Figure 3–44 DRUM RIGIDITY EFFECT ON BRAKE GAIN (Ref. 9)

TABLE 3–25. PRESENT STATUS OF VARIOUS DISC BRAKE WEAR SENSORS

Manufacturer	On-Board Sensor	Type	Location	Remarks
General Motors	Yes	Squealer	Inboard pads	Not all models
Ford	No	-	-	Pending
Chrysler	Yes	Growler	-	Discontinued in 1973
Toyota Corona	Yes	Electrical	Inboard pads	-
Volkswagen				
Beetle	No	-	-	Pending
Dasher	Yes	Pulsing pedal	-	-
Sirocco	Yes	-	Outboard pad	-
Volvo	No	-	-	Hamilton-Standard doing research
Renault	Yes	Electrical	Inboard pads	-
Porsche	Yes	-	-	Increased pressure
Audi	Yes	Electrical	Distance between pads, and fluid level	-
BMC (late models)	Yes	Wire noise makers*	-	-
Peugeot	Yes	Electrical	Inboard pads	-
Citroen	Yes	Electrical	All pads	-
BMW	Yes	Electrical	Fluid level	Increased pressure
Saab	Yes	Electrical	Fluid level	Increased pressure
Mercedes	Yes	Electrical	Fluid level	Increased pressure

*Doubles as an anti-rattle spring.

A. PRODUCTION VERSIONS

Electrical Sensors

Electrical systems are used to give a visual or audible indication to the operator within the vehicle. Sensors may be broken down into three categories:

- Make on fault
- Break on fault
- Proportional

Make on Fault

'Make on fault' sensors may be as simple as a wire embedded in the friction material (Figure 3-45). As the friction material wears away, the wire becomes exposed and contacts the rotor which is connected to vehicle ground. Some systems have an insulated contact button on the shoe that contacts the rotor in a like manner.

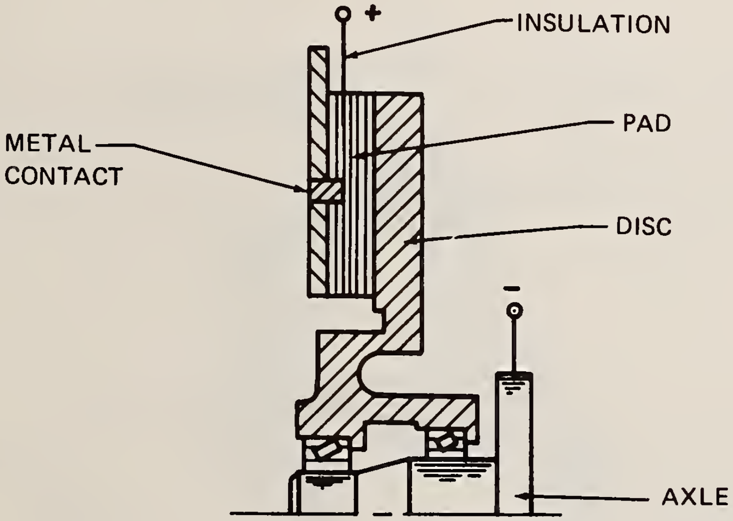

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Figure 3–45 INDICATION BY SHORT CIRCUIT VIA THE AXLE

More sophisticated 'make on fault' sensors use reed switches and magnets attached to the shoe. When the pad wears down to the danger point, the switch is pulled closed by the magnets and indicates a fault (Figure 3-46).

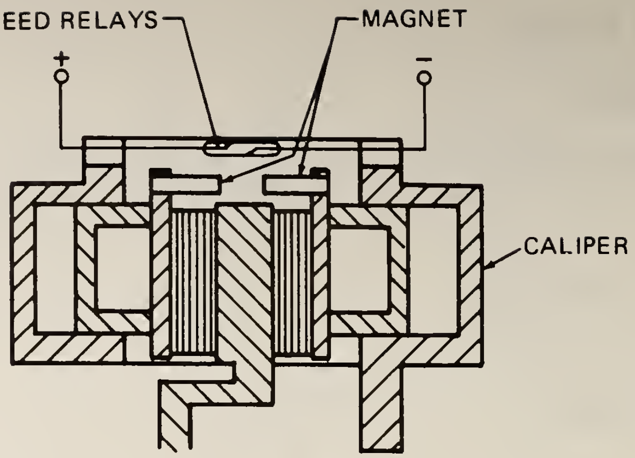

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Figure 3—46 INDICATION BY DRY REED RELAY (Ref. 33)

Monitoring piston travel by sensing hydraulic pressure (Figure 3-47) is still another way of 'make on fault' to indicate friction material wear.

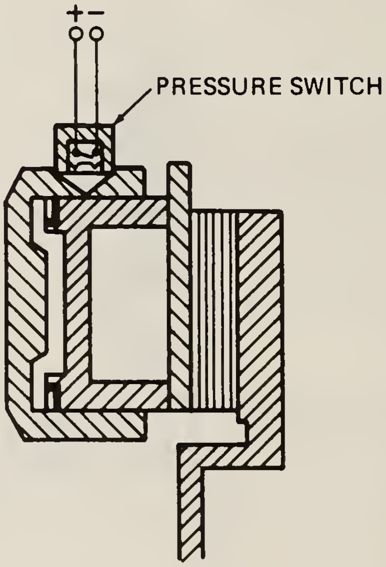

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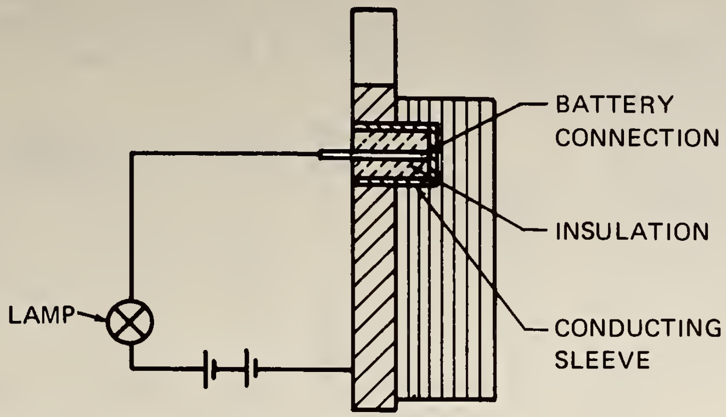
Figure 3—47 INDICATION BY PRESSURE SWITCH (Ref. 33)

A dual contact system may be embedded in the shoe (3-48). As the friction material wears away, both contacts are exposed and the rotor completes the circuit.

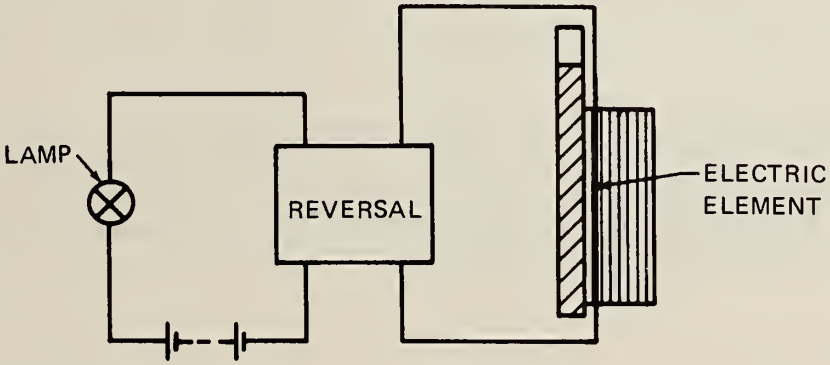


86-2682

Figure 3–48 INDICATION BY CLOSING A CIRCUIT THROUGH THE DISC

Break on Fault

'Break on fault' electrical systems require a reversal device such as a relay or a transistor to change state to the indicator (Figure 3-49). This system has the advantage that it is fail safe; i.e., if a wire breaks in the circuit, the alarm is given as a brake system failure. A single wire may be embedded in the friction material. As the material wears away, the wire is opened and the reversal actuates the indicator.



86-2683

Figure 3–49 INDICATION THROUGH CHAFING THROUGH A WIRE

A sensor that monitors both pads simultaneously consists of a breakable element mounted between the two disc pads (Figure 3-50). When either of the pads wear to their limits, the single sensor is fractured and indicates a fault. A more complicated microswitch in the same location could also be used as either a 'break or make on fault' indicator.

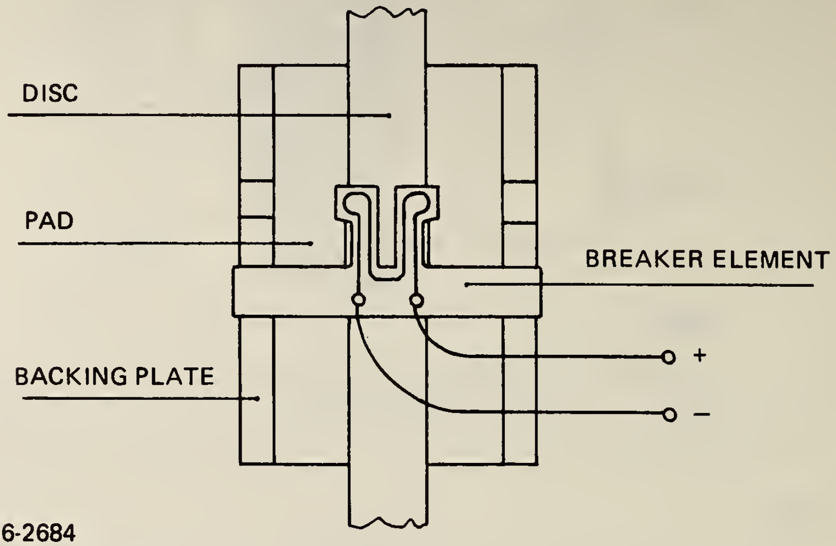


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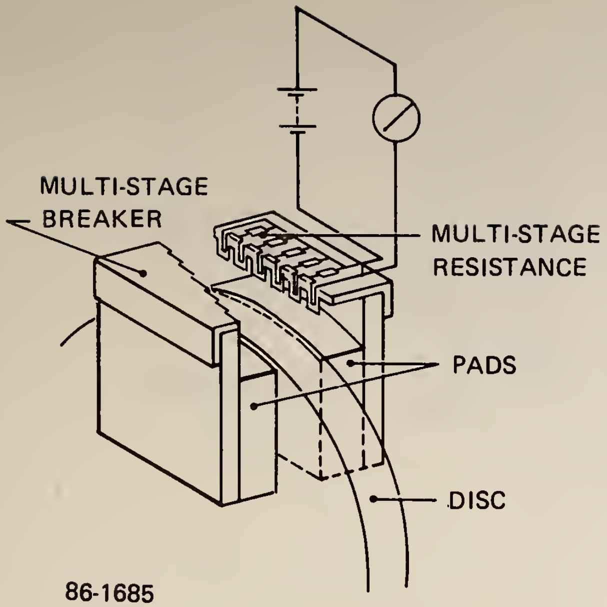
Figure 3–50 INDICATION BY CONTACT BREAKER (Ref. 33)

Proportional

Proportional pad wear sensors give a continuous indication of the condition of the pads either by the wheel (Figure 3-51) or by the pad (Figure 3-52). Each sensor must be monitored separately to get maximum information, series or parallel combinations may mask a single fault or cause a false alarm. The system like the 'break on fault' system is fail safe in that if a wire breaks the unit will indicate a system failure.

Fluid level in disc brake systems is also proportional to disc pad wear. A fluid level sensing switch in the brake fluid reservoir may indicate when the pads are worn excessively. This type of warning may easily be defeated by a consciencious mechanic, topping off the brake fluid as a matter of routine maintenance.



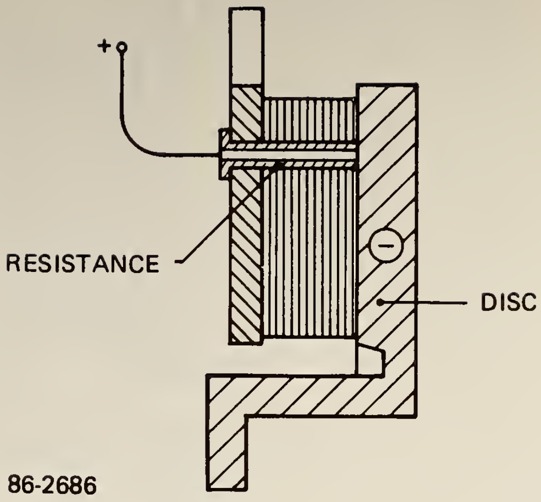


Figure 3–51 PROPORTIONAL INDICATION BY MULTISTAGE RESISTANCE (Ref. 33)

Figure 3–52 PROPORTIONAL INDICATION BY SHORT CIRCUIT (Ref. 33)

Acoustical Sensors

In an effort to reduce costs of transmission lines and visible indicators, audible sensors have been devised. They may be broken down into three basic categories: growlers, squealers, and rattlers.

The growler type audible alarm is often a bent tab on the brake shoe that contacts the moving element away from the normal braking surface (3-53). The low frequency rumble or growl indicates that the friction material has worn beyond safe limits whenever the brakes are applied.

Similar to the growler are some of the squealer indicators. They work on the same principle but consist of a flat shaped finger that rubs on the rotor and emits a high pitch squeal. (See Figure 4-2.)

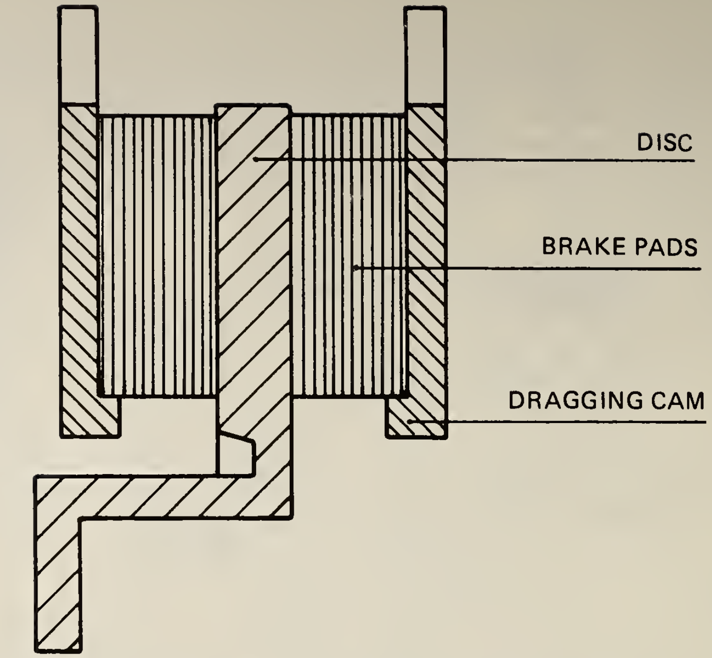


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Figure 3–53 INDICATION BY SCRATCHING METAL (Ref. 33)

One other squealer type system consists of a material between the safe usable friction surface and the backing that will squeal when the brakes are applied (Figure 3-54).

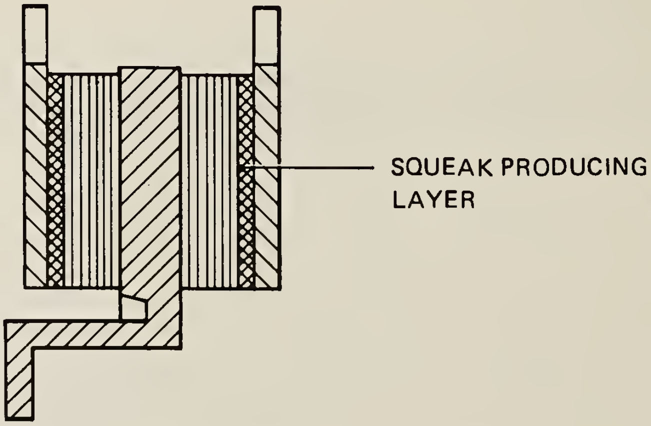

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Figure 3–54 INDICATION BY SQUEAK (Ref. 33)

Rattler sensors give a distinctive noise that is perceptable in the vehicle. A typical rattler device consists of tabs on the disc pad that strike the edge of the disc and give a low frequency noise (Figure 3-55).

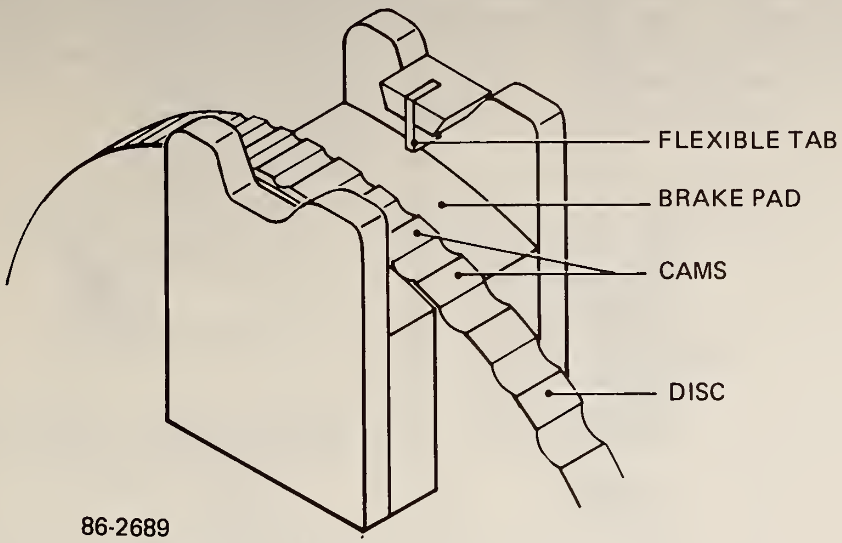

Figure 3–56 INDICATION BY ACTUATING A SOUND ELEMENT (Ref. 33)

A ball may be released to strike and rattle against whatever it finds due to vibration of the wheel (Figure 3-56). This tethered noise maker will be released by a push pin as the friction material wears away.

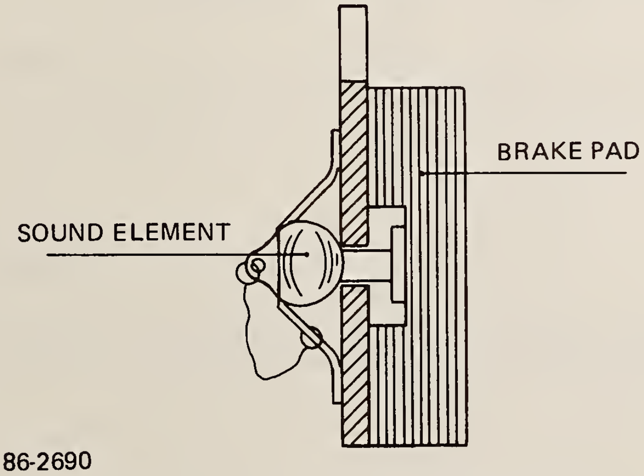

Figure 3–55 INDICATION BY HIGH FREQUENCY RATTLING (Ref. 33)

Mechanical Sensors

Mechanical systems to indicate friction material wear use a mechanical linkage to actuate the indicator. This is most commonly in the form of a flexible cable. The indicator may be a visual indicator (Figure 3-57) or an audible alarm (Figure 3-58) which is amplified by using the backing plate as a sounding board.

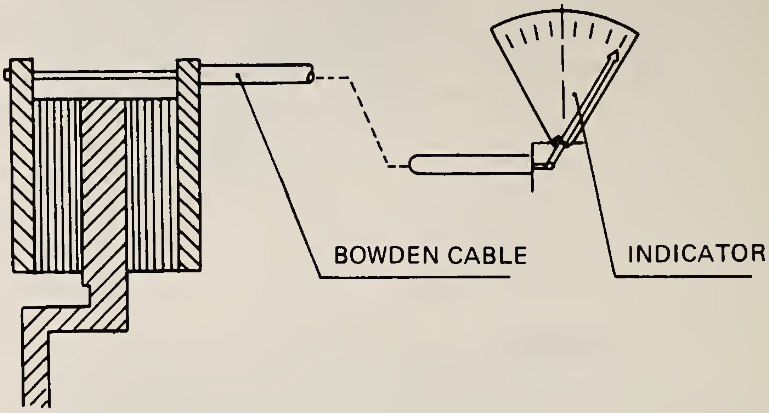

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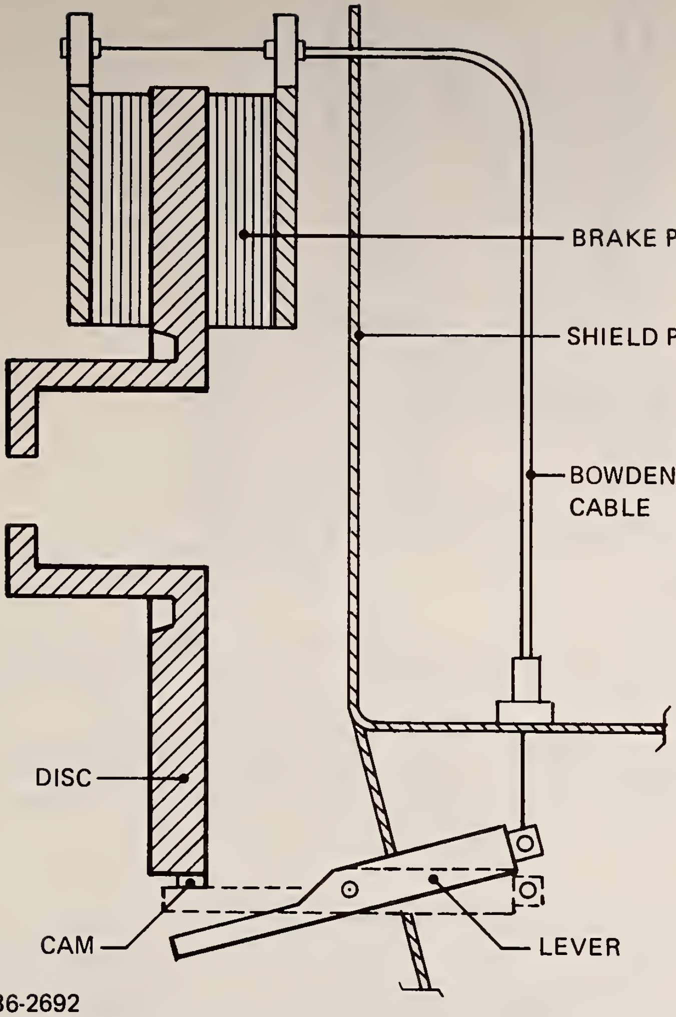
Figure 3–57 INDICATION VIA BOWDEN CABLE (Ref. 33)



86-2692

Figure 3–58 INDICATION BY THE BACKING PLATE (Ref. 33)

Smoke/Smell Sensors

These sensors indicate by means of an odor or a cloud of smoke when the pads have worn down to the replacement level (Figure 3-59).

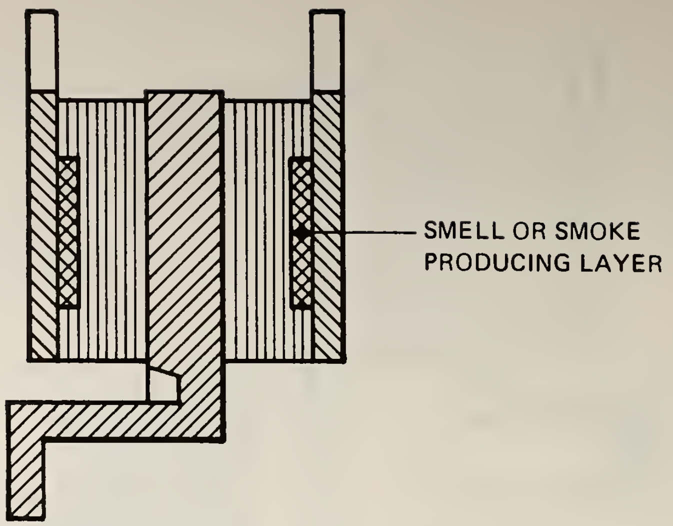


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Figure 3–59 INDICATION BY SMELL OR SMOKE (Ref. 33)

Visual Wear Indicators

Some systems that do not indicate to the driver lining material wear, but are visibly accessible to a mechanic or inspector have been proposed.

One such system has an indicator that is engaged with the caliper and follows the pads (Figure 3-60). Wear limits are indicated on the caliper and a quick visual inspection can determine the amount of wear left in the pads.

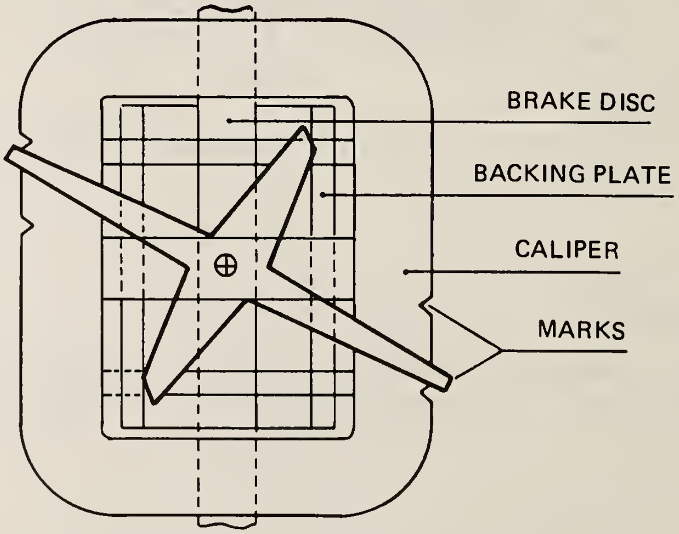

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Figure 3–60 INDICATOR IN THE CALIPER (Ref. 33)

Another visual wear indicator has a dye embedded in the lining and when the friction material wears away, the disc is marked (Figure 3-61).

Still another visual wear indicator has been proposed. This consists of a simple indicator machined into the pad. The mechanic must be able to visually inspect the indicator (Figure 3-62).

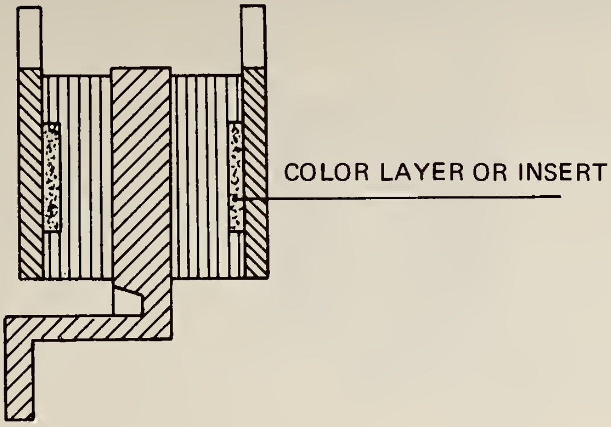

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Figure 3–61 COLOR INDICATOR (Ref. 33)

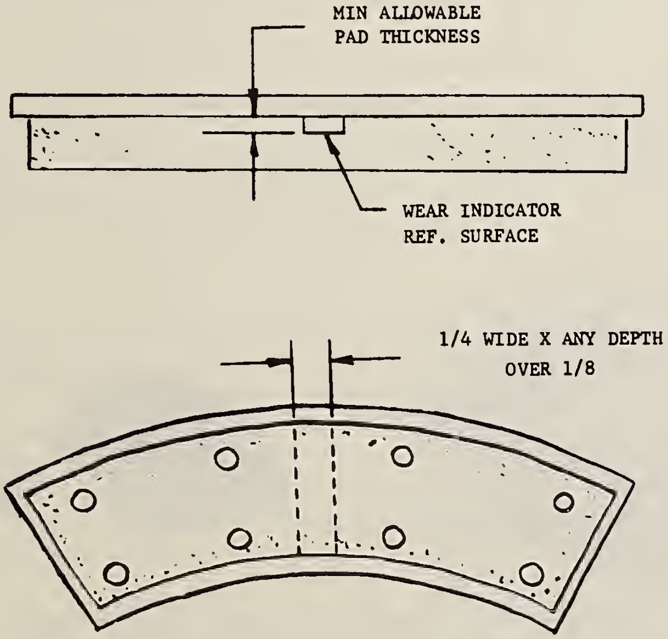

Figure 3–62 STATIC BRAKE INSPECTION (Ref. 34)

Pedal Feel Indicators

Various systems for indicating to the driver via the brake pedal when a pad needs replacement exist. One method uses a lower coefficient of friction material that reduces the gain at the faulty wheel (Figure 3-63) This causes wheel pull at the steering wheel and higher pedal forces. A similar method is employed by reducing the gain with a spacer that causes the pad to tilt with reduced efficiency.

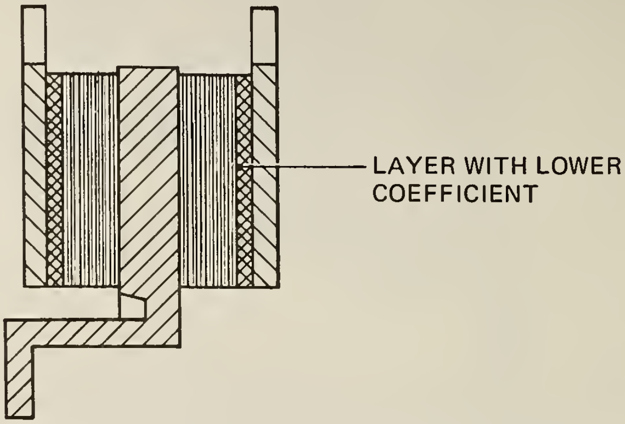

Figure 3–63 INDICATION BY REDUCTION OF BRAKE EFFICIENCY (Ref. 33)

One other tactile method is to cause the pedal pressure to pulsate. The efficiency is reduced for a short part of a revolution and causes a pulsating sensation in both the steering wheel and the pedal (Figures 3-64 and 3-65).

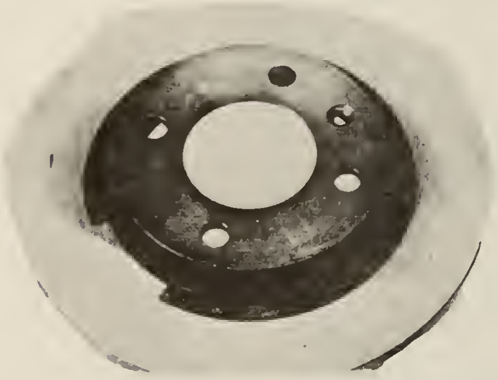

Figure 3–64 NEW AND WORN PAD FOR TACTILE INDICATOR (Ref. 33)

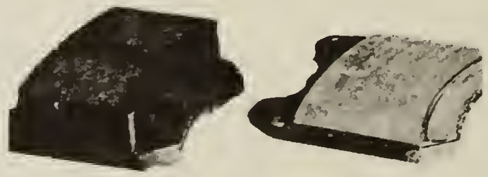

Figure 3–65 BRAKE DISC FOR TACTILE INDICATION (Ref. 33)

Discussion

The relative merits of various sensing techniques was the subject of a recent SAE paper by Hattwig of Volkswagen (Ref. 33). The author's assessment of the candidate techniques as applied to VW cars is shown in Table 3-26. Industry dialog has confirmed the general conclusion that the tradeoff lies between sensor cost and reliability of the indication. This applies both to the choice of the generic approach and to its specific application. Two key issues are placement of the sensor and the propensity of the system to produce false alarms.

The false alarm problem arises with electrical systems of the fail-safe type - sensors are designed to give a failure indication if disconnected or broken. The Audi sensor has been reported as particularly subject to false alarms, although the sensor is of the non-fail safe variety. It would appear that the problem is a design detail, rather than a generic problem of electrical sensors. False alarms are also a problem with audible sensors in the sense that "normal" squealing of the disc brakes is sometimes mistaken for a failure indication. Conversely, the failure to differentiate between the audible failure indication and in-use squealing presents a problem in providing a proper warning of impending wear-out.

The placement of the warning indicator is another key issue. Several manufacturers have elected to place the wear detection device on the in-board pad only. For single piston brakes, which utilize a sliding or floating caliper to apply the pad to the opposite side of the disc, this appears to be a valid approach. Uneven wear, if it does occur, will almost inevitably occur more rapidly on the inboard (piston side) pad. General Motors, in fact, has begun using harder and/or thicker inboard pads to equalize the useful life of a pad set. One would expect, however, that this practice, by rendering the expected life of the pads approximately equal, would create the possibility of the outboard pad wearing out first.

In addition to the problem of whether to instrument one or both pads, there is also a question of where the indicator should be placed on a specific pad. The ideal indicator would be sensitive to insufficient pad thickness at any point. This capability is approached by the Rover electrical sensor, which utilizes a pair of electrical wires imbedded in the pad. For indicators that are sensitive to pad thickness at a point or along a line, allowance should be made for reasonable variations in pad taper. (Figure 3-66.)

The condition of uneven wear has been observed on a number of occasions in imported cars, and General Motors is believed to allow for up to 1/8 inch taper (end-to-end) in their pads. Accommodation for uneven wear of this magnitude would require a warning threshold significantly higher than would be required if wear were uniform.

TABLE 3-26. COMPARISON OF PAD WEAR CONCEPTS

	Costs	Reliability	Clarity	Unmistakableness	Utility value*	Accuracy
Electric systems in general	-	0	+	+	+	0/+
Acoustic systems in general	+	+	-	-	0	+/-
Indication by a pointer in the caliper	+	+	-	+	-	0
Indication via Bowden cable	-	0	+	+	0	-
Indication by smell or smoke	+	+	-	-	0	+
Color indication	+	+	-	-	-	+
Indication by reduction of brake efficiency	+	+	-	-	0	+
Tactile indication	+	+	+	0	0	+

Meaning of signs: + good, 0 passing, - could be better

*automatic indication
possibility of proportional indication
possibility of automated readout

Source (Ref. 33)

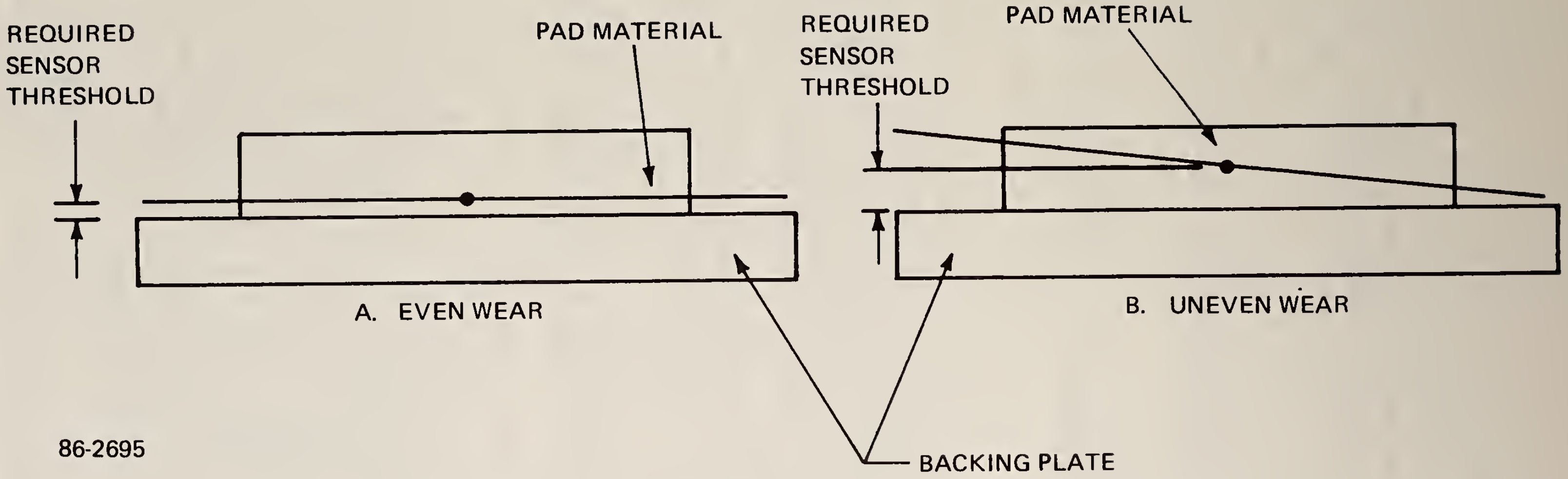

Figure 3–66 EFFECT OF UNEVEN PAD WEAR ON THRESHOLD REQUIREMENTS

3.2.7.4 System Tradeoffs

The currently available information on all of these questions (false alarms, response to various types of failure indication, and extent of uneven wear in disc brake pads) is basically qualitative. For this reason, the effectiveness of the various techniques will be treated parametrically. The maximum accident cost savings to be used in our analysis will be $60 (Table 3-4). To this we must add the maximum possible economic savings. Table 3-7 shows that as much as $35 may be recoverable over the vehicle lifetime, if 70% of disc/drum replacement and 50% of refinishing is eliminated. The total potential benefit is $95.

The next step is cost estimation for representative sensors. Four types will be considered: two squealers and two electrical.

Squealers

A set of replacement General Motors Guardian brake pads with squealers retails for $14.15 or $3.54 per pad. On the basis of a factor of three mark ups, each pad has an OEM cost of approximately $1.15. It is estimated that the squealer cannot cost more than $.10 OEM or $.30 for replacement parts. If three sets of brakes are used in the automobile's lifetime then the total cost would be approximately $1.80.

The continuous squealer type is estimated to cost some four times as much as the GM squealer for a lifetime cost to the consumer of $7.20.

Electrical Sensors

The electrical wear devices are significantly more costly.

a. Make wire sensor - light goes on when bared wire contacts brake disc.

Price for a set of four Peugeot pads of which two have sensors is $14.15. It is estimated that sensors cost some 15% of the set of pads thus each sensor costs approximately $14.15 x 15% or $.53 each. If an average vehicle uses three sets of pads in its lifetime then the sensor costs a total of $3.18 per vehicle. In addition to the sensors, there is a display at about $1.00 OEM and some 20 feet of wire at $.01 per foot plus connectors for an estimated total of $.60. With an OEM cost factor of three and a maintenance factor of 50% (on the display cable only) the total lifetime cost is estimated to be:

Brake pads = $3.18

Display + cable $1.60 x 3 x 1.5 = 7.20

Total $10.38

b. Break Wire Sensor - light goes on when wire in friction material is worn through and electrical continuity is broken.

It is estimated that because there are two leads as opposed to one, the cost of sensors will be 50% greater than the make wire sensor thus the lifetime sensor costs will be approximately \$3.18 x 1.5 = \$4.77.

The display costs should be about the same while the wire and connector costs will about double thus the system lifetime cost is estimated to be:

Sensors = \$ 4.77

Display - 1.00 x 3 x 1.5 = 4.50

Cable + Connectors = 1.20 x 3 x 1.5 = 5.40

Total \$14.67

It should be noted that each Toyota break wire sensor retails for \$13.81 thus, if the sensors are worn through with each pad change (this probably will not happen all the time) and three sets of pads are used in the car lifetime then the total cost would be 6 x \$13.81 = \$82.86 plus display and wiring or in excess of \$90. It is felt that this cost is highly inflated by the Toyota marketing philosophy and does not reflect the true cost of these sensors. Thus this data is ignored.

The tradeoff between the four sensor concepts is illustrated in Figure 3-67. It can be seen that all four concepts have a break-even effectiveness substantially below the 55% level, which was established as a bench mark for sensor effectiveness on the basis of driver awareness in the Indiana study.

In Task 2, it was determined that wear sensors should also be evaluated in an off-board readout mode. In this instance, the evaluation is quite simple. Based on the estimated costs, the electrical sensor concepts are clearly competitive with wheel removal for lining thickness inspection, since the direct labor associated with wheel removal is on the order of \$.25/wheel, (3 man minutes at \$5/hr) or \$1.00/year for all four wheels. The elimination of the in vehicle display would reduce the sensor costs to under \$12 for even the most complicated sensor. However, it must still be determined whether wheel removal is required to conduct other inspections or whether the entire process of lining thickness inspection will evolve to procedures like those developed in the Static Brake program, (Contract DOT-HS-4-00949) in which it is shown that lining thickness inspections can be conducted without wheel removal, providing certain vehicle design changes are adopted. Although off-board readout is feasible, real-time readout also appears to be cost-feasible, and is the preferred approach.

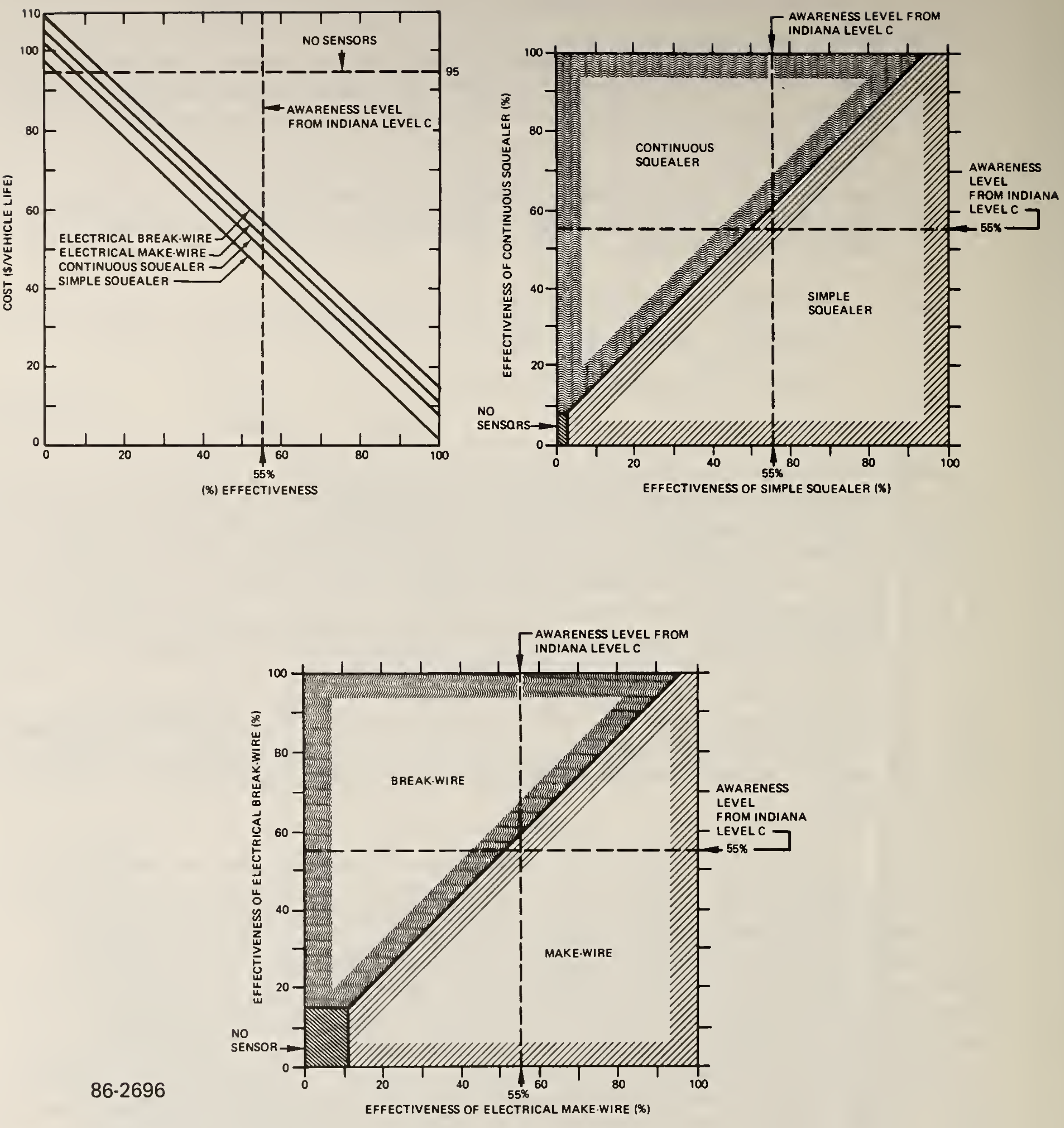

Figure 3–67 TRADEOFFS BETWEEN PAD WEAR SENSORS

3.2.7.5 Recommendations

Although the most complicated sensor costs more than 8 times as much as the simplest, it (the most expensive sensor) must be only 13% more effective to yield a greater benefit. This is considered to be possible, in view of the significantly improved display. It is therefore impossible to determine which sensor is preferable.

It should be noted that the cost-benefit analysis of pad and lining wear sensors is more favorable than that of any sensors considered in this study. This is a result of two factors: low sensor cost and high estimated benefits. Of these factors the estimated costs are probably the easier to defend. The accident benefit calculation is based almost exclusively on accidents involving drum brakes and the maintenance benefit is based on conjectured savings. The recently completed Diagnostic Inspection Demonstration Projects (Title III) should have collected data on whether diagnostic information has made any impact on the service practices in the brake repair industry. If little or no impact is found on the frequency of drum/disc refinishing and replacement due to brake diagnosis, the predicted maintenance savings for wear sensors may not materialize.

3.2.8 Brake Fluid Leak Sensor

3.2.8.1 Review of Justification

The accident statistics indicate that brake fluid leaks which have led to lining or pad contamination are causal factors often enough to justify further pursuit in terms of on-board sensors. This, moreover, is one of those rare but pleasant instances where the sensor can actually warn the driver before the danger is actually present. In addition to the obvious accident prevention benefit of a device which warns the driver of impending brake lining contamination, an effective leak warning sensor should also enable the owner to replace leaking seals or cylinders before the leak has reached the lining and, hence, before the linings have to be replaced.

It should be observed, however, that fluid leaks leading to contamination were confined to drum brakes within the Indiana study. Other sources have also indicated that fluid leaks (from caliper piston seals) do not pose a problem for disc brakes. Hence, the need for fluid leak detection may be confined to rear wheel brakes, as the use of front disc brakes becomes universal. Moreover, the propensity of wheel cylinders (on drum brakes) to leak appears to be related to the chemistry of the brake fluid, rubber seals, and the metals used in the system. Improvements in these areas may likewise eliminate the problem for drum brakes.

A further comment on the occurrence of leaks in the Indiana data is that in a number of cases, the leak apparently developed shortly after the brakes were relined. This apparently occurs because the operation of relining involves exposing the wheel cylinder pistons to damage from corrosion products that have accumulated outside the normal working range of the piston seals. Routinely replacing or rebuilding wheel cylinders when relining is performed should prevent this problem from occurring. There appears to be insufficient evidence to determine whether, or under what special conditions, this practice should be encouraged, recommended, or mandated.

3.2.8.2 Functional Requirements

The Indiana cases give only a qualitative assessment of the amount of contamination in each case. It is significant, however, that in only two cases was the loss of fluid sufficient to require a "low fluid" citation upon inspection of the master cylinder reservoir. Based on the Bendix studies, (Refs. 9 and 10) a reasonable quantitative requirement would be the detection of a 5-10 cc (1 to 2 teaspoons) loss of fluid. Inasmuch as lubricant contamination of friction surfaces was a nearly-qualifying sensor area in Task 2, it would be highly desirable for a sensor of brake fluid to be sensitive to similar quantities of bearing/axle grease or oil, as well.

3.2.8.3 Candidate Sensing Techniques

Based on the criterion established, one approach that is probably non-viable is detection at the master cylinder. The volume of fluid displaced as a set of disc/brake pads is worn vastly exceeds the fluid loss that must be detected. For a 3.1 inch caliper piston (typical of Bendix brakes on large Ford cars), the volume of fluid displaced as the pads are worn 3/8 of an inch (out of 7/16 original thickness) on two front brakes is 186 cubic centimeters, which is 18.6 times the required threshold. For drum brakes, the calculations are less horrendous. With a one inch wheel cylinder, 0.030 inch clearance on either shoe, and properly working adjusters, only 1.6 cc are displaced at each actuation. If the allowable clearance is increased to 0.060 inch, 3.22 cc are displaced. Implementation of a sensor in the master cylinder would require redesign of the reservoir to detect fluid level changes in the rear circuit only. In addition, a chamber would be required that makes the float, or other level sensing device, insensitive to shock and vehicle acceleration. In addition, the sensor would have to be "trimmed" by adding fluid until slightly above the fault threshold each time the brakes are serviced. If all this is done, a float-type sensor would detect excess operating clearances (malfunctioning adjusters) as well as non-contaminating hydraulic leaks (e.g., broken brake lines) in the rear circuits. However, the costs to re-design the master cylinder reservoir and to provide such a system are probably prohibitive.

At the other end of the brake line, i.e., at the wheels, an ideal leakage sensor would also work for bearing or axle oil or grease, so that the same one (or a similar one) can also look after the potential problem of bearing seal failure. Chemical "sniffers" might fit with the requirements if one could be found to react with equal enthusiasm to mineral oils and to one of the constituents of brake fluid. However, no such devices are known to exist. Indeed, the Static Brake Inspection Investigation program* (Ref. 34) found no such method available for brake fluid alone, much less fluid plus oils.

Another possibility, besides a chemical detector, might be a switch designed to be actuated by the surface tension of any liquid. This would have the advantage of working equally well with any of the three probable contaminants rather than having to find a sniffer for each, or one that will work for all three.

A wheel cylinder in a brake drum is much more likely to start leaking at the bottom and, hence, the obvious place for a leak detector is just outside the bottom of the wheel cylinder boot. However, this is not the only place a leak could start and neither axle nor hub seals seem to display any marked preference for any particular location at which to start leaking. A better solution might be a collecting boot which both gathers all the leaks into one concentration, the better to be detected, and leads it away from the brake linings to a place where it can do no harm. This would both improve the effectiveness of the sensor and offer a precaution against the driver of the car not paying attention to the warning. This is essentially the solution proposed in Ref. 34. (Figure 3-68)

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*Contract DOT-HS-4-00949

3.2.8.4 System Tradeoffs

It can be argued that it is the design feature of collecting and diverting contaminating substances away from the shoes, rather than any sensor that might be used to detect their presence, that offers the real payoff. Moreover, the question is academic, inasmuch as no practical sensing technique is currently available.

The accident cost data from Tables 3-4 and 3-10 are as follows:

	All Cases	Unaware Only
Fluid Leaks	$48.65	$28.09
Lube Leaks	30.60	19.84
Both Combined*	$50.56	$30.00

*Derived from Table 2-11.

Inspection of Table 2-11 indicates a large degree of overlap between cases involving fluid and lubricant contamination. That is, of the four cases cited for lubricant contamination, three were also cited for brake fluid contamination at the same or other wheels. This probably indicates a general lack of maintenance of the vehicles involved, as well as a conservatism on the part of the investigators in citing only the vehicles in the worst condition.

If attention is restricted to rear brakes only, the totals become:

	All Cases	Unaware Only
Fluid Leaks	$10.01	$10.01
Grease Leaks	17.63	9.05
Both Combined	$27.64	$19.06

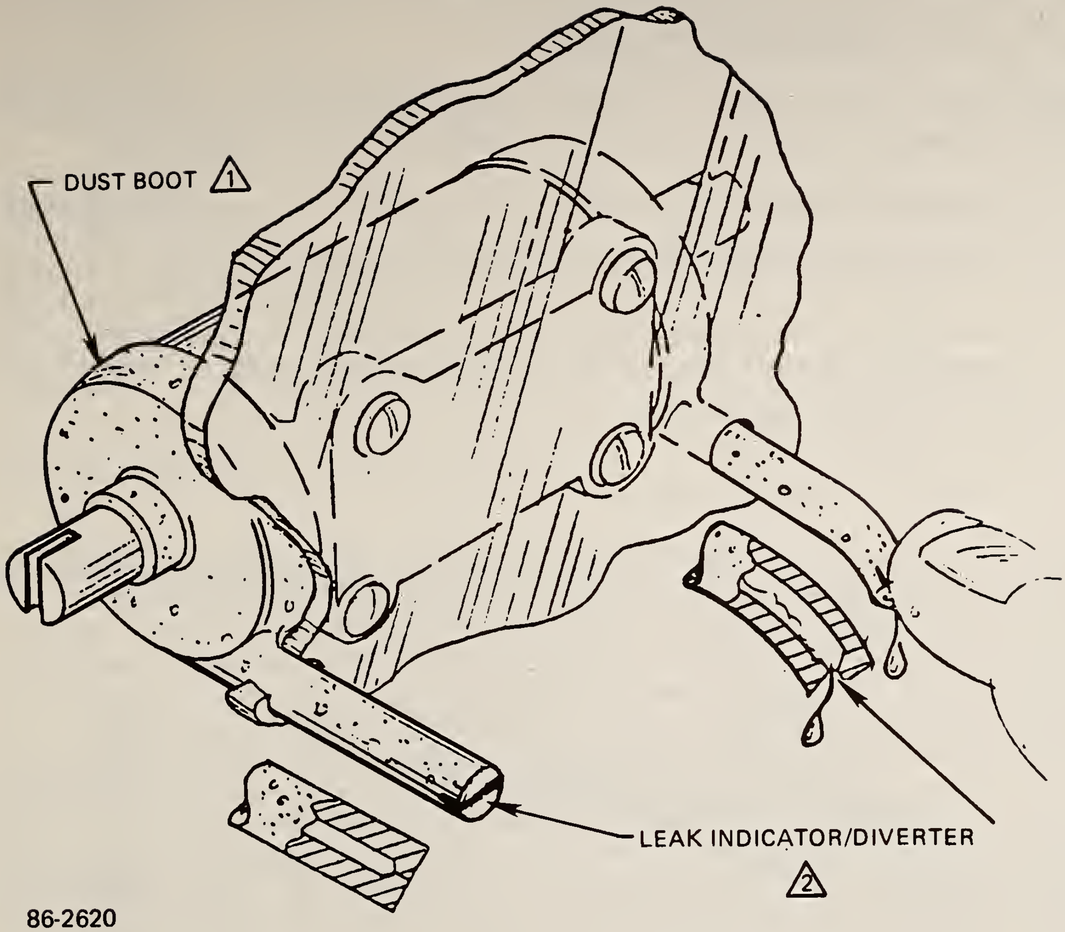


Figure 3–68 VISUAL LEAK INDICATOR/DIVERTER FOR DRUM BRAKE WHEEL

However, this table may be somewhat optimistic in view of several cases in which the front brakes were also defective, and the defects at the rear were probably not the principal problem.

3.2.8.5 Recommendations

Inasmuch as no viable sensor candidates have been devised, it is impossible to recommend one. The salient findings of our inquiry are:

1. Brake fluid leaks occur almost exclusively in drum brake systems.

2. Improved drum brake designs may eliminate the problem.

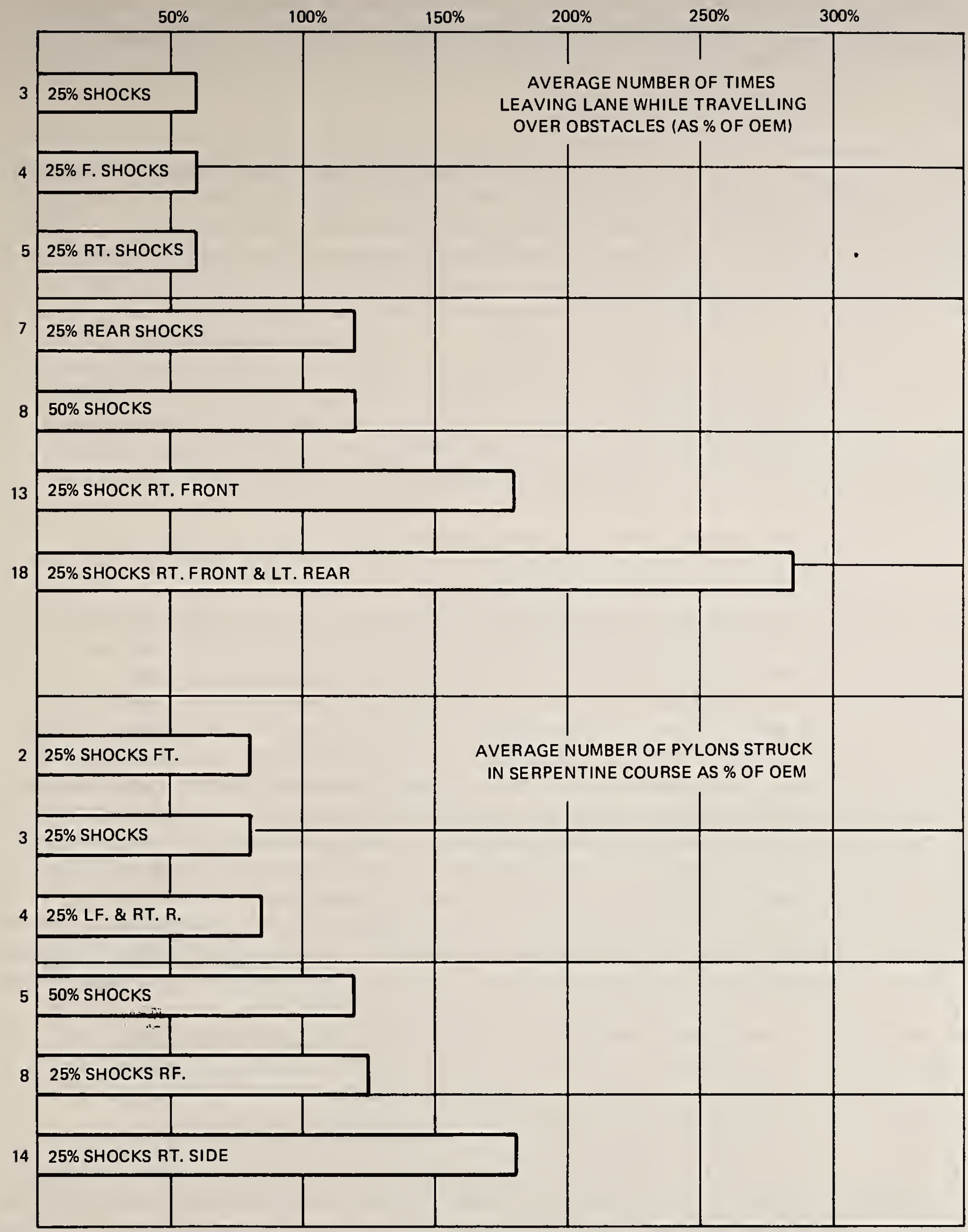
3. Redesign of the pushrod boot into a collector/diverter for fluid leaks should take care of the rest of the problem.

3.2.9 Shock Absorber Sensors

3.2.9.1 Review of Justification

Indiana's accident data does little to indicate that damper deterioration does much in the direction of causing or contributing to accidents. Clayton's study (Ref. 35) tends to show the contrary. Clayton's method was to measure the performance of a vehicle with 21 faults or combinations of faults. Their methods of measurement were, first to count the number of times the vehicle left its lane while traversing a bumpy course and to compare this number with the performance of the OEM vehicles; second, to count the pylons struck during the negotiation of a serpentine course and to compare this with OEM performance. A percentage reduction in damping (precise definition is by resistance/stroke curves at three different oscillation speeds: 4, 100 and 200 strokes/min. and the peak resistance at each speed is compared with the OEM to obtain the percent deterioration) is used as a criteria and Monroe made available sets of dampers with 25, 50, and 75% loss of resistance. Seven combinations were tested on the bumpy course and on the serpentine course. In both cases, some types of deterioration resulted in improved performance. A 25% loss on all four dampers and on only the front pair showed quite a marked gain over OEM's condition, but there was not much uniformity after that. Fifty percent loss all around produced about 20% deterioration in controllability (as defined by Clayton's method). A summary of these tests is shown in Figure 3-69.

It is possible that these tests may say more about the selection of OEM damper valving than it does about the effect of deterioration, but it says enough about the latter to justify further examinations of onboard sensors for shock-absorbers.


50%
100%
150%
200%
250%
300%
AVERAGE NUMBER OF TIMES LEAVING LANE WHILE TRAVELLING OVER OBSTACLES (AS % OF OEM)
3 25% SHOCKS
4 25% F. SHOCKS
5 25% RT. SHOCKS
7 25% REAR SHOCKS
8 50% SHOCKS
13 25% SHOCK RT. FRONT
18 25% SHOCKS RT. FRONT & LT. REAR
AVERAGE NUMBER OF PYLONS STRUCK IN SERPENTINE COURSE AS % OF OEM
2 25% SHOCKS FT.
3 25% SHOCKS
4 25% LF. & RT. R.
5 50% SHOCKS
8 25% SHOCKS RF.
14 25% SHOCKS RT. SIDE

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It should also be pointed out that, unlike brake performance deterioration, dampers do not provide tangible evidence of their degradation to accident investigations.

3.2.9.2 Functional Requirements

Shock absorber testing on the vehicle has not yet reached an equivalent level to brake testing. External test methods are limited to forced frequency and consequent resonance damping on the one hand and oscillation on the other. Machines by Koni and Sama test the latter after a wheel drop of 4 inches; Hunter and Boge apply an external excitation at the suspension's resonant frequency, and then monitor either the control force (Hunter) or the amplitude (Boge). Both these methods suffer from the assumption that damper performance is uniform at different speeds and that a test in one mode is sufficient. Tracor Jitco, who recently completed a study for NHTSA on the four testers (Ref. 36) concludes that the Boge does the best job. They also concluded that: "shock absorber inspection using any technique is only marginally effective economically."

3.2.9.3 Candidate Sensing Techniques

Unfortunately, these test machines do not really offer much that can be applied to on-board sensors. The basic function of a damper is to offer resistance to suspension movement in a way roughly proportioned to the velocity of that movement. Thus, measurement of the force transmitted to the chassis of the car by the damper would provide the basis. Software and other sensors could probably be devised which would result in the damper force resistance only being measured when suspension input factors were right; this would be complex and expensive. Alternatively, the car could be given some predetermined test, such as a 4 inch drop while the on-board sensors were coupled to an off-board readout. The reading would be compared to that particular car's specification to reach a decision on whether it should be passed or not. It might prove necessary in practice to use two or perhaps more different drop heights to secure adequate suspension movement velocities; or it might be necessary to apply a forced frequency to supplement the drop test. A test and development program should yield this kind of information. One limitation of the method is that, although the sensor need only read a fairly moderate force, perhaps it will remain attached during much greater force applications and must not be damaged by them.

Any drop-test or forced frequency test suffers from the inevitable inaccuracies caused by non-standard tires, under-inflation or unusual compliance in suspension vertical movement. The total energy input may be the same, but it will be applied during an increased time if, for example, the tire is under-inflated during a drop-test. In fact, since the tire rate is decreased, the distance dropped by the sprung mass would be greater than if the tires were correctly inflated and the tests of damper compression would therefore be modified. This aspect may well have been researched by the tester manufacturers and/or by Tracor Jitco, but it would have to be re-examined during any test program.

Moreover, the need for sophisticated testing of any type has not been established vis-a-vis the simplest tests possible: the standard "bounce-test", in which the inspector depresses the car and observes its motion, and the visual inspection of shock absorbers for leaks. Although loss of fluid is not the only failure mechanism, it has been estimated to be responsible for about 50% of the safety problem.

3.2.9.4 System Tradeoffs

An estimate for the provision of four load cells and the necessary harness to provide a central off-board readout connection is about $20.00 per car in production. This, spread over 10 years of semi-annual inspections works out to $1 per year. Compare this to about $30.00 per car per inspection (or $60.00 per year), according to the Tracor Jitco analysis.* While these figures are not all that close, they are at least of the same order, and the on-board sensor provides several obvious advantages even over and above the probability of more accurate readings. However, both of these costs are far above the estimated lifetime cost of shock absorber induced accidents ($9.27) from Table 3-4.

3.2.9.5 Recommendations

The application of on-board load cells offer a significant performance advantage over current test techniques, inasmuch as the tire can be eliminated from the dynamics. The problems of providing a suitable excitation to the vehicle remain. However, the deficiency of the simpler manual inspection techniques must be better documented before more advanced techniques can be justified. In addition, the documentation of accident costs associated with shock absorber deficiencies must be substantially strengthened.

3.2.10 Tire Integrity Sensor

3.2.10.1 Review of Justification

Tire integrity did not qualify as a candidate area based on the Indiana investigations. Indeed, tire failures have never been cited as an accident causal factor throughout the Indiana study. However, tire failures are known to be a contributor to vehicle disablement from a number of turnpike studies. (Figure 2-8) See also Sections 2.2.2 and

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*These numbers apply to test methods requiring that shock absorbers be removed from the vehicle.

2.2.3. In addition, tire failures were cited in the California Highway Patrol study of vehicle factors in fatal accidents.

3.2.10.2 Functional Requirements

The relationship between observable tire defects and the expected life of the tire is not well known. Tire manufacturers do not routinely study the progress of structural defects and the eventual failure of the tire. Moreover, much of their life testing is conducted at an accelerated rate, in which the tire is more severely stressed than it would be in normal use. It can only be stated that the rejection standards for periodic, visual inspection of tire condition are based on common sense.

3.2.10.3 Candidate Sensing Techniques

Although it might be desirable to provide a sensor capable of indicating the structural condition of tires, there are no practical methods of doing so known at this time. Tire industry representatives have indicated a belief that the vast majority of in-use tire failures are precipitated by running the tire underinflated. The heat build-up resulting from underinflation causes tire structural failure rather than some incipient structural flow in the tire. In this respect, tire inflation sensors could conceivably have a large impact on the problem of tire failure.

The techniques for off-vehicle tire integrity testing (without application of a sensor within or on the tire) are currently under development. Work has been performed by DOT to develop tire integrity testers for new tires, inspection of tires prior to recapping and most recently for periodic inspection of tires while mounted on automobiles. This latter work, which is being performed by South West Research under contract to DOT involves developing a tire integrity sensor for on-line periodic motor vehicle inspection use in the District of Columbia lane. The tester utilizes resonant vibration techniques, and requires no on-board sensors to aid in off-board readout. The capability of the devices are listed in Table 3-27. The operating principles are described in Figure 3-70. Vibrations at a resonant mode frequency are applied to the center of the tire tread by a roller driven by a shaker. Receiving transducers (accelerometer) are mounted in the same radial plane at equal distances from the sources transducer. The vibrating properties of the tire and the vibrating symmetry of the radial cross section are measured. The tire is rotated about its circumferential axis with the source held stationary.

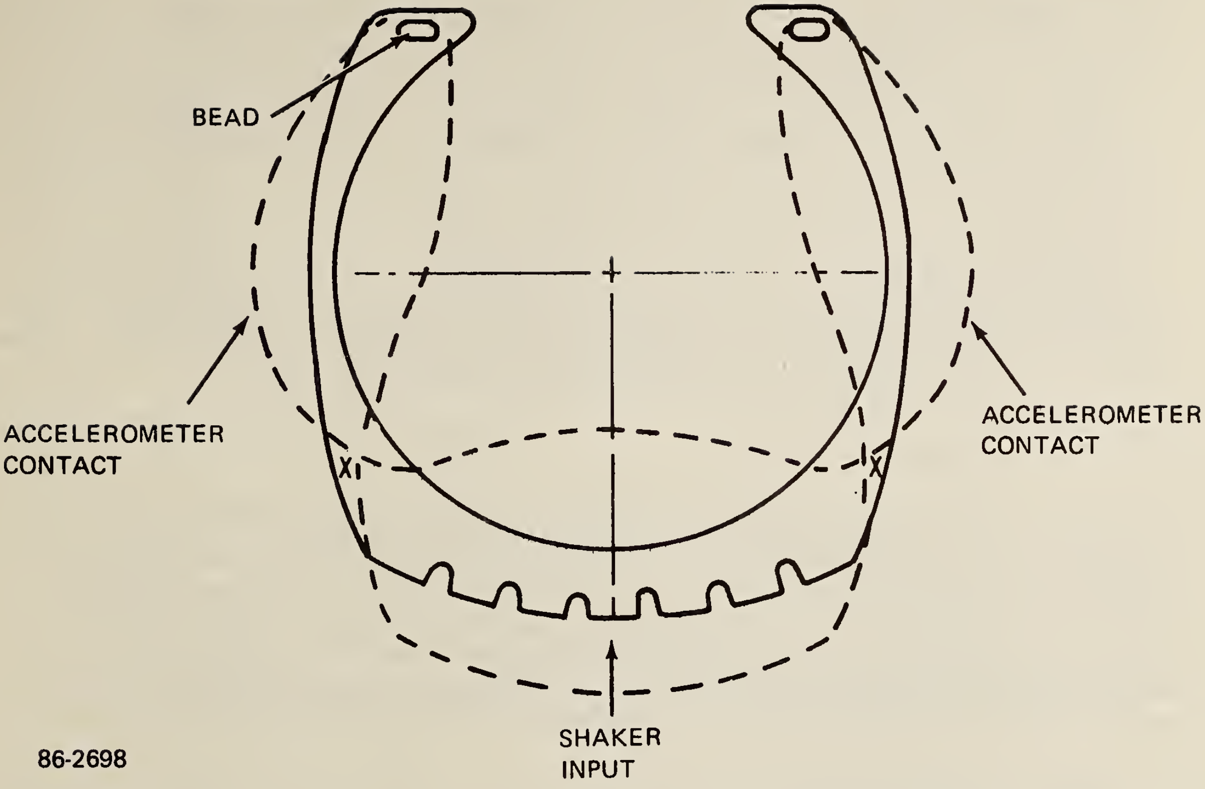


Figure 3–70 RESONANT VIBRATION TECHNIQUES FOR TIRE INTEGRITY TESTING

TABLE 3–27. TIRE DEFECT DETECTABILITY – OFF VEHICLE TEST TECHNIQUES

Defect	Size	Location	Detectability
Separations	1" and larger	Sidewall, tread	Very good
Separations	Smaller than 1"	Sidewall, tread	Good-poor
Separations	1" and smaller	Shoulder area	Poor
Cut (into ply)	2" and larger	Sidewall	Good
	2" and larger	Shoulder	Poor
Scuff (severe)	2" and larger	Sidewall	Good-poor
Chunk out	2" and larger	Tread area	Good
Patches and plugs		Tread area	None

Note: Defects which were symmetrical about the circumference of the tire were not detectable such as a circumferential break in the belt.

3.2.10.4 Tradeoff

There are no on-board sensor concepts, practical or otherwise. The estimated lifetime accident cost due to tire failure of $4 (Table 3-4) suggests that any sensor must be low in cost. At 12 tires per vehicle life, and 100% effectiveness, the breakeven cost for a sensor would be $.33. If consideration is given to estimates that underinflation induced failures account for 50-90% of the problem, the allowable sensor cost is still further reduced, to between 3.3 and 16.7¢ per tire.

3.2.10.5 Recommendations

The only hope of justifying further work on auto tire structural failures as an accident cause would be to show that they figure far more importantly in serious accidents than they do in the overall accident picture.

On the basis of existing information, on the contribution of tire degradation in accidents, and the absence of any cost effective methods for sensing tire degradation, it is recommended that no further effort be made in this sensor development.

3.2.11 Front-End Alignment Sensor

3.2.11.1 Review of Justification

It has not been possible to justify any kind of sensor or sensors on the grounds of accident statistics. What data there is, is on limit performance. For example, Reference 6 found that:

> "Misalignment of front wheels to the virtually maximum level achievable, has been shown to contribute a significant alteration in limit lane change performance..."

However, primary justification for the provision of on-board sensors, with either on-board or off-board readout, would be a consumer's benefit. Car owners now have to rely on front-end checks when either tire wear or driving behavior indicate the possible presence of defects. Thus, the stable door is almost never closed until some time after it has become apparent that the horse has gone. On-board sensors with on-board readout would (or could) give the driver warning of an out-of-spec condition before any damage is done. Similarly, an off-board readout could provide an owner with information of value to him if he went to a shop with the readout equipment. Off-board readouts would also provide an easier and improved PMVI method. However, since most PMVI systems look only at toe or "scuff", no direct comparison can be made.

3.2.11.2 Functional Requirements

It would be necessary for whatever device was selected to:

- sense when the car was level.
- sense camber angle of each front wheel.
- sense the toe angle of each front wheel to the vehicle axis from 0 to 10° in or out.

The system would have either to be given external instructions on when each reading should be taken or it could have an internal program so arranged that the readings would be taken every time the circumstances were right, and the data either displayed and updated continuously or held available on demand. For off-board readout, the same sensors (i.e., car level, wheel camber on each wheel, steer angle on each wheel) would be required, but the computations could be carried out manually, semi-automatically or fully automatically.

3.2.11.3 Candidate Sensing System

No candidate systems offer themselves. It would undoubtedly be possible to use electronic vials attached to various parts of the car for car level and the two camber readings, provided one was prepared to accept the assumption that the wheel camber and the angle of the front-suspension upright were inextricably connected. Similarly, a specially made heli-pot or some similar device could be arranged to give toe angle, with respect to a control arm.

3.2.11.4 Tradeoffs

While this approach is technically possible, it is very expensive. Electronic vials cost over $1.00 per unit and minimum quality potentiometers were costed at $4 (OEM) in Section 3.2.5. Since a total of 5 sensors is required (3 levels and 2 pots) the minimum possible per car cost for equipment alone is of the order of $5.00, OEM. Applying the usual factor of three, we obtain $15, exclusive of wiring. Since most shops charge about $12 to $15 for a front-end check, (some charge less if no adjustment is made) the cost of the sensor hardware would equal three years worth of normal alignment checks (Hunter's Service Job Analysis (Ref. 22) indicates that, on average, each car has an alignment once every three years). However, the cost of providing alignment checks in a PMVI lane is much lower. Table 3-9 shows that alignment checks in a lane have an equipment cost of only $0.49 per year.

3.2.11.5 Recommendations

On-board sensors for alignment may make sense only where high capacity equipment for inspection is not available. The determination of how they might fare under these conditions would require an expensive feasibility study.

3.3 SUMMARY OF RESULTS

Eleven candidate areas for sensor application were identified in Table 2-14 as worthy of detailed study. One of the primary objectives of this task was to identify sensing techniques for each of these eleven candidates. Four different categories of results have been identified:

1. Sensor techniques existing - available in today's marketplace.
2. Sensor techniques possible - not currently available, but can be projected from devices available today.
3. Indicator techniques possible - not truly a sensor, but passive devices to indicate condition.
4. Nothing forseeable - no feasible indicators or sensors uncovered.

The status in each candidate area is described in Table 3-28. Only one out of the eleven candidate areas has been found non-inspectable using sensors or indicators.

A second major objective of this task was sensor evaluation. This has taken the form of a cost-benefit analysis. The calculation of potential safety benefits culminated in Table 3-4, and the calculation of economic benefits, in Table 3-7. Individual sensor cost estimates are developed throughout Section 3.2. The results of these exercises are shown in Table 3-29, along with comments for each of the sensor concepts.

Of the five areas considered for on-board readout (six counting brake lights as two areas) existing hardware was found in three (4) areas. Three (4) areas were also determined to have potentially favorable benefit cost ratios. However, the lists of three were not identical. Tire inflation sensors, although they have received considerable attention and development for truck applications, do not yet appear ready for application to passenger cars. A significant cost reduction is required. On the other hand, the sensing of brake performance with low cost semi-conductor strain gages placed at strategic places in the brake assembly, although not previously described in the literature, appears feasible.

Among those sensors considered for off-board readout, the possibilities for cost-effective inspection techniques are more limited. Among the "true" sensors, pad and lining wear is the leading candidate. However, this sensor appears to be even more effective with on-board readout. Brake performance inspection using on-board sensors appears attractive only when dedicated test equipment is not available. Improved tire tread depth indicators may be cost-effective, but additional research is required.

TABLE 3–28. RESULTS OF ON-BOARD SENSOR IDENTIFICATION

Candidate area	Sensors exist	Sensor technically possible	Indicators technically possible	Nothing foreseeable
Brake performance		X		
Tire pressure	X			
Brake light optical	X			
Tire tread			X	
Steeering play		X	X	
Brake light electrical	X			
Brake pad/lining wear	X			
Brake fluid leak			X	
Shock absorber		X		
Tire integrity				X
Front end alignment		X		

TABLE 3–29. SUMMARY OF SENSOR EVALUATIONS

	Max payoff					
	Safety	Economic	Sensor cost	Breakeven % effectiveness	Comments	Potential for favorable B/C
			Candidates for on-board readout			
Brake performance	$129	11	$36-53	30-38%	Concept development recommended	Yes
Tire pressure	39	28	185	100+	Significant cost breakthrough required	No
Brake light	5	--		100+	Major uncertainty in payoff	Yes
Pad/lining wear	60	35	$ 2-15	2-15%	Data base principally on drum brakes	Yes
Brake fluid leak	49	--	N/A	N/A	No workable concept Vehicle redesign possible Data base uncertain	N/A
			Candidates for off-board readout			
Brake performance	129	21	$30	31-55%	May make sense for appointed garages Costs high with dynamic test machines	Yes No
Tire tread	46	--	?	?	Improved indicator - additional research recommended	Yes
Steering wheel	10	--	$18	100+	Improved PMVI preferred concept	No
Pad/lining wear	46	35	$ 2-15	3-21%	On-board readout preferred	Yes
Brake fluid leak	41	--	N/A	N/A	Improved indicator/vehicle redesign	N/A
Shock absorbers	9	--	$30	100+	Safety justification questionable	No
Tire integrity	4	--	N/A	N/A	No workable concepts Data base uncertain	No
Alignment	2	5	$15+	100+	Concepts identified marginal in performance	No

4.0 DISPLAY CONSTRUCTION

Two static and one active display units were provided as a part of the effort on the contract.

Figure 4-1 - Tire Inflation Sensors

This display includes the TYRECHECK inflation test system and two General Motors valve stem sensors. One of the latter provides an indication of tire pressure through the use of a spring loaded plunger.

Figure 4-2 - Brake Pad Wear Sensor

This display includes the following:

- The electrical break-wire type sensor. An example of a Toyota brake pad with sensor installed is shown.
- The electrical make-wire type sensor. An example of a Peugeot brake pad with sensor is shown.
- A brake pad with a General Motors type squealer is shown. The squealer makes a noise only when the brake is activated.
- A brake pad sensor that makes a continuous noise when the pad lining becomes too thin. This type is not now in use on any vehicle.

Figure 4-3 - Light Failure Sensing System

The active display includes operational demonstration models of:

- The Cadillac fiber optics system.
- The current sensing system proposed by Avco which meets all the requirements of the specification set forth in Table 3-22.

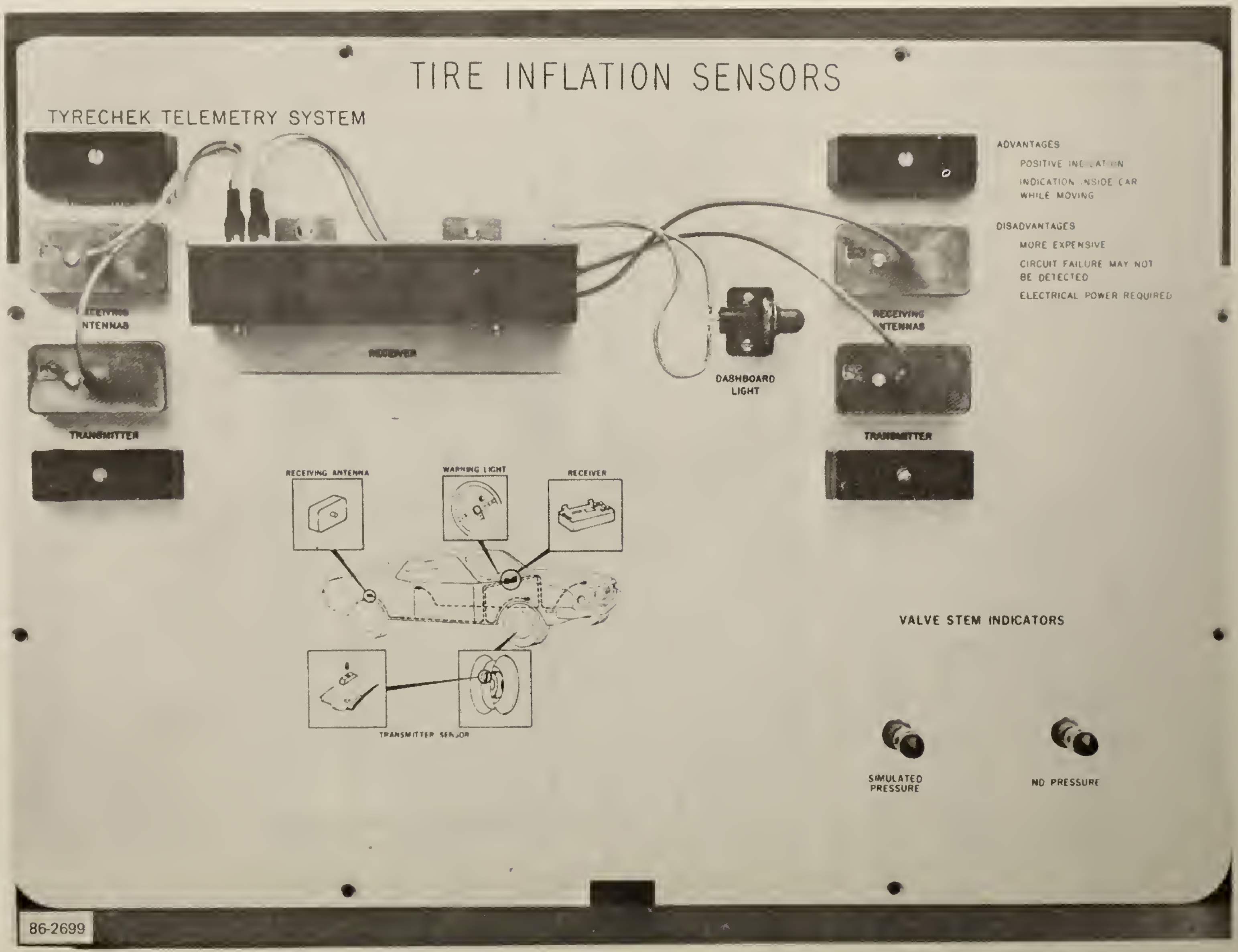
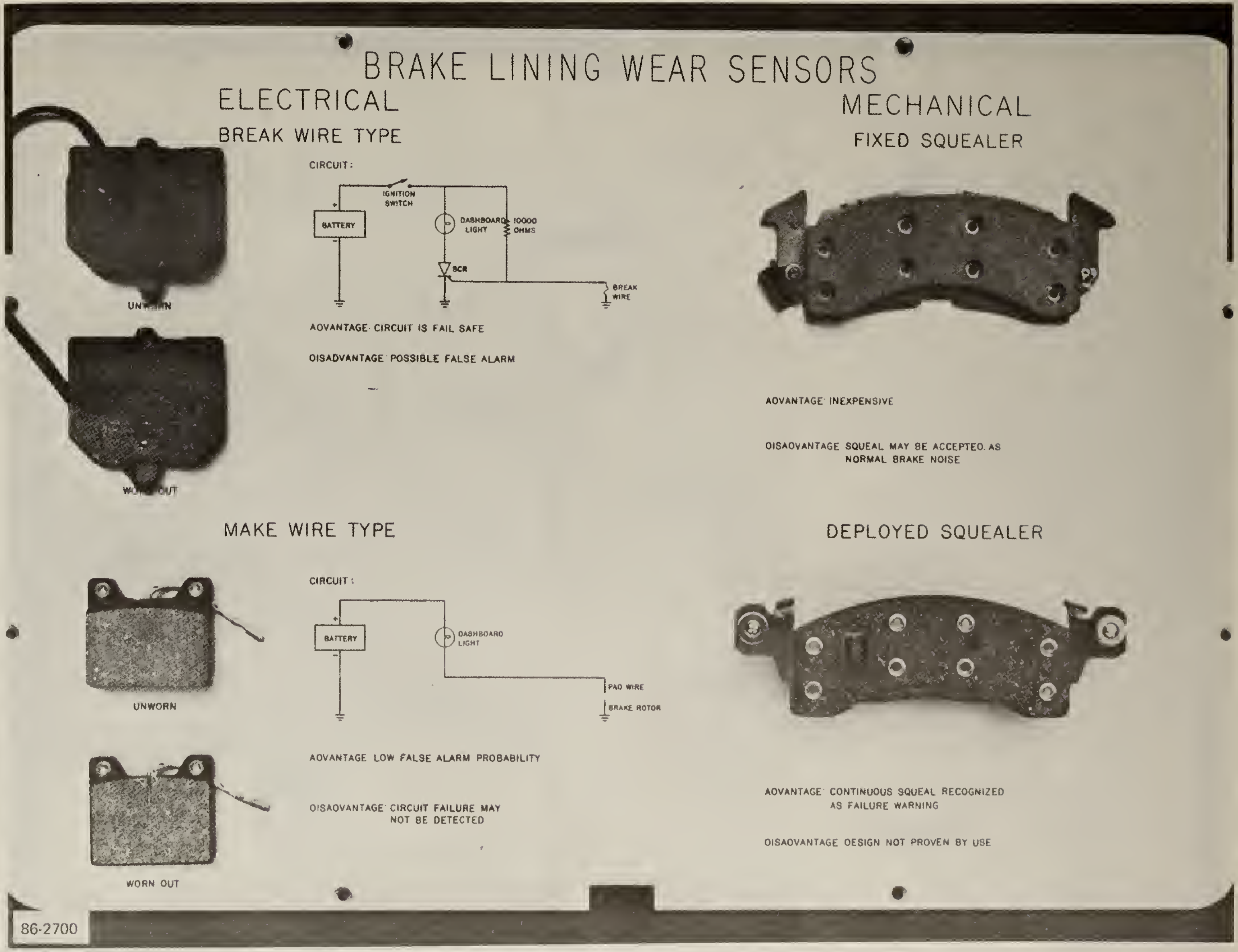


Figure 4–1 TIRE INFLATION SENSOR



BRAKE LINING WEAR SENSORS

ELECTRICAL

BREAK WIRE TYPE

ADVANTAGE: CIRCUIT IS FAIL SAFE

DISADVANTAGE: POSSIBLE FALSE ALARM

MAKE WIRE TYPE

ADVANTAGE: LOW FALSE ALARM PROBABILITY

DISADVANTAGE: CIRCUIT FAILURE MAY NOT BE DETECTED

MECHANICAL

FIXED SQUEALER

ADVANTAGE: INEXPENSIVE

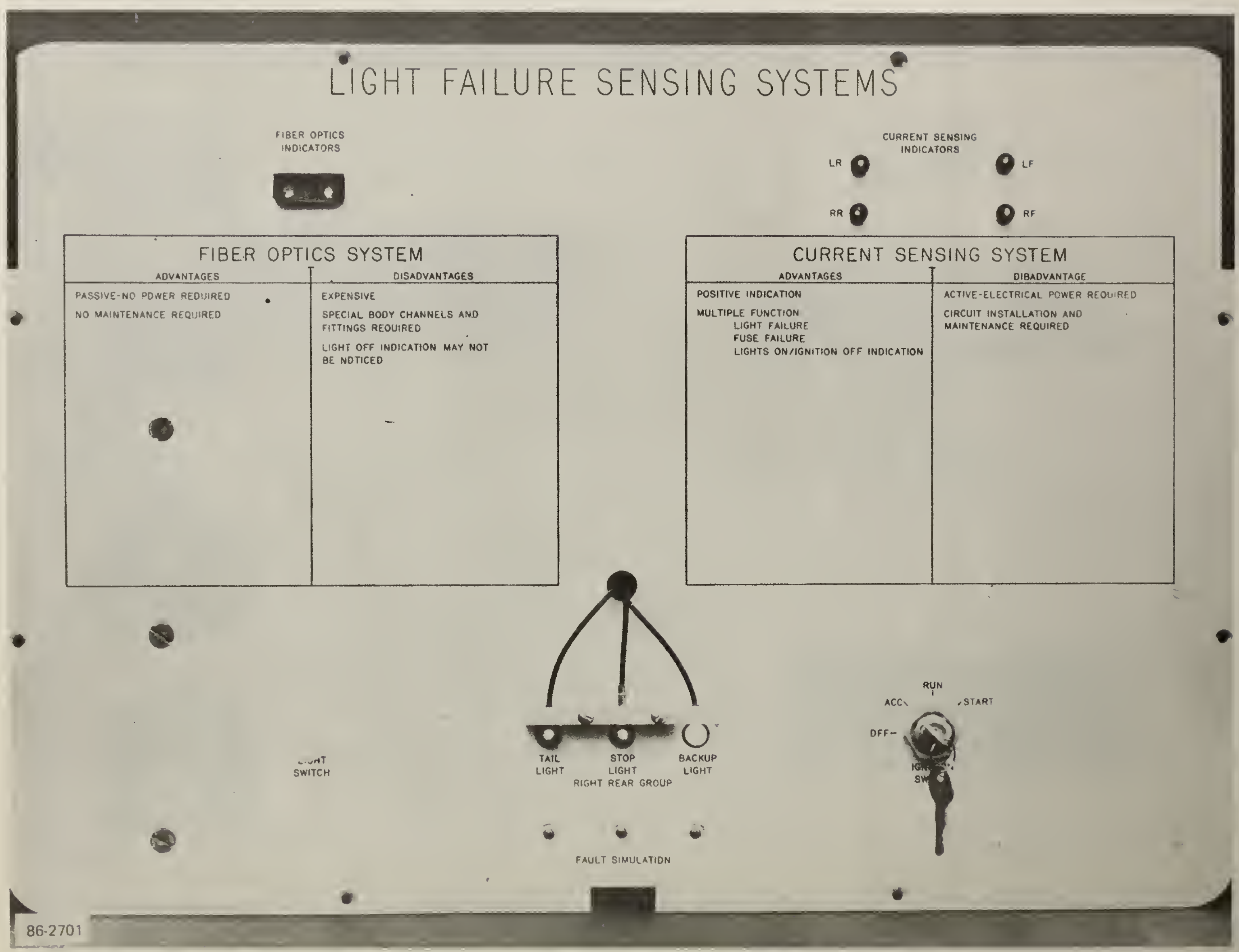
DISADVANTAGE: SQUEAL MAY BE ACCEPTED AS NORMAL BRAKE NOISE

DEPLOYED SQUEALER

ADVANTAGE: CONTINUOUS SQUEAL RECOGNIZED AS FAILURE WARNING

DISADVANTAGE: DESIGN NOT PROVEN BY USE

Figure 4–2 BRAKE LINING WEAR SENSORS



FIBER OPTICS SYSTEM

ADVANTAGES	DISADVANTAGES
PASSIVE-NO POWER REQUIRED	EXPENSIVE
NO MAINTENANCE REQUIRED	SPECIAL BODY CHANNELS AND FITTINGS REQUIRED
	LIGHT OFF INDICATION MAY NOT BE NOTICED

CURRENT SENSING SYSTEM

ADVANTAGES	DISADVANTAGE
POSITIVE INDICATION	ACTIVE-ELECTRICAL POWER REQUIRED
MULTIPLE FUNCTION LIGHT FAILURE FUSE FAILURE LIGHTS ON/IGNITION OFF INDICATION	CIRCUIT INSTALLATION AND MAINTENANCE REQUIRED

Figure 4–3 LIGHT FAILURE SENSING SYSTEMS

5.0 CONCLUSIONS

The conclusions of this study are of two basic types. Those of the first type relate to the requirements of the Statement of Work and to specific on-board vehicle sensors -- whether they are cost-beneficial, what development work is required, and whether other regulatory action is indicated. For purposes of discussion, these conclusions are labeled "Technical". Conclusions of the second type, although not required by the Statement of Work, are potentially more important, inasmuch as they impact the validity of the former. These conclusions are the outgrowth of a self-critical review of this study including both its methods and results. Although they are also technical in nature, these conclusions are labelled "critical".

5.1 TECHNICAL CONCLUSIONS

- Utilizing a criterion of applicability in 1/2 of one percent of cases in the Indiana Tri-Level Studies in Accident Causation, (Level C investigations, Phases II-V) on-board vehicle sensors are indicated in the following areas:

    - Brake performance.
    - Tire (under) inflation.
    - Tire tread depth.
    - Brake light (electrical or optical).
    - Steering wheel play.
    - Brake pad and lining wear.
    - Brake fluid leak onto friction material.

- Based on limit performance studies, shock absorber sensors are also indicated.

- Based on criticality of failure mode and data on failure frequency, tire integrity sensors are indicated.

- Based on the possibility of consumer economic benefits, an on-board vehicle sensor for front end alignment qualified for further consideration, although not qualifying under any other criteria.

- The scope of areas considered for sensor application has been restricted to the brake, tire, steering, suspension, lighting and signaling systems. Other sensors may be indicated in other areas.

- In the eleven candidate areas considered, sensors have been found on currently available production automobiles in the following areas:
  - Brake light intensity (Cadillac).
  - Brake light function (Toyota, Honda).
  - Brake pad wear (GM, Volkswagen, Audi, Peugot, others).
- For all of the remaining areas, except tire integrity, it has been possible to postulate a sensing technique that would perform the function required. In some cases, however, the techniques identified are conceptual in nature, and would require additional study to determine their feasibility.
- A preliminary cost benefit analysis has indicated that a favorable benefit-cost ratio may exist for the following sensor concepts:
  - Brake performance.
  - Brake lights.
  - Brake pad and lining wear.
  - Tire tread depth.

5.2 CRITICAL CONCLUSIONS

In addition to fulfilling the requirements of the Statement of Work, the work performed under this contract has led to some general conclusions about the strengths and weaknesses of the data bases that have supported it. These conclusions are of fundamental importance, since all conclusions drawn relative to specific sensor concepts can be no stronger (and no more valid) than the foundations upon which they rest.

The principal conclusion we have reached is that the data base in all areas critical to this study is weaker than expected. These weaknesses have significantly compromised the strength of the conclusions reached.

It was recognized at the outset of this program that the data base was imperfect. The multi-stage algorithm used in determining the candidate areas represents an attempt to compensate for these deficiencies. The preferred method of analysis would have been to consult a definitive source on the role of defects in accidents (one based on a number of actual accident investigations) and to answer directly the question: "Is this specific vehicle condition a significant contributor to accidents?" However, at the outset of this program, it was believed that certain types of defects would not be detectable through direct accident investigation, and it was deemed necessary to employ other considerations.

Experience, however, has indicated that the combination of accident data sources with laboratory and analytical sources has been somewhat impractical, insofar as the development of quantitative information is concerned. The following sections represent an attempt to identify the sources of difficulty.

5.2.1 Accident Causation

Our principal data source on accident causation (Indiana) is of generally high quality in the scope of defects identified. This program has relied heavily on the Indiana Study as a source of data on sensor applicability. However, as a data source for any broadly based judgments in the VIU area, the Indiana investigations have six major limitations:

1. Small sample size (only 420 Level C cases).

2. Limited currency (present and future automobiles differ in important respects from those studied).

3. Limited generality (although Monroe county, Indiana, is average in many respects, it does not offer a sufficiently wide range of driving environments to be representative of the entire nation).

4. Interactive effects are present (the Indiana PMVI program may be affecting vehicle condition in ways that make extrapolation difficult to a non-PMVI environment or to a different inspection system.

5. Unresolved technical contradictions exist between the investigative data and laboratory experience.

6. Data quality is not perfect. (A minor, rather than major limitation is the questionable judgment in a few specific cases. This may relate more to the documentation than the actual judgments themselves.)

Note that most of these limitations have been caused by conditions beyond the control of NHTSA and the Indiana personnel, and should not be construed as a criticism of either organization. It is believed, however, that this data base lacks the strength required to support rulemaking.

5.2.2 Limit Performance

Studies have attempted to define the relationship between defective/ degraded components and the capability of the man/vehicle system to perform accident avoidance maneuvers. Areas of investigation reviewed in this study were brakes, tires, steering, and suspension systems. As a general comment on these studies, it was found that vehicles and drivers tended to perform better in the laboratory than real world experience might have suggested. There appear to be fundamental difficulties in creating simulated emergencies in which to study the vehicle driver system. This does not mean that limit performance studies should not be performed or that they should be ignored. Rather, it suggests that the results of these studies must be interpreted before they are applied to the real world. The principal user of these studies, therefore, should be the accident investigator. He is ultimately responsible for deciding whether laboratory findings on the effects of tire under-inflation are applicable in any specific case. Thus, the relevance of laboratory research must constantly be determined in the light of typical accident scenarios. We find that the interface between theory and practice has not been fully exploited during recent years.

5.2.3 PMVI Effectiveness

This subject is an area of current activity in which the authors are heavily involved. We hope that our biases are not exposed too strongly by stating that the results of ongoing work will greatly improve the state of knowledge in this area.

5.2.4 Vehicle Component Degradation Rates

One of the major unanswered questions raised in this study concerns the relationship between the present and future condition of the vehicle. What is the probability distribution of elapsed time between an incipient brake fluid leak and a total failure? A 3 psi underpressure and a 5 psi underpressure? A detectable tire defect and a blowout? A steering system free-play of 10° and a play of 20°? A 20% shock absorber degradation and an 80% degradation? Until these questions are answered, it is difficult to set optimal inspection standards and intervals, or reasonable detection criteria for onboard sensors.

5.2.5 Motorist/Driver Interface With the Repair Industry

Justification for several of the sensor concepts may well rest on the gains achievable through improved diagnosis. The processes currently operating are not well understood. For example, considerable evidence is available to indicate that insufficient tire pressure is a common defect on American automobiles. Several studies have shown that about 25% of all cars have at least one soft tire. However, there is virtually no data on how these vehicles arrive in this condition. No one seems to know whether the American motorist checks his tire pressure once a week, once a month, or once a year. No one seems to know how often he should check tire pressure to maintain an adequate level of safety. As a result, it is impossible to predict the effect and the effectiveness of tire inflation sensors for passenger cars: how often they will give alarms, and how the motorist will respond to such an alarm.

5.2.6 Response of Drivers to On-board Sensors

Data uncertainties exist in three key areas:

1. The effectiveness of certain sensors in making the alarm perceptable to the driver (e.g., brake squealers).

2. The effectiveness of sensors in communicating the need for corrective action.

   Example:

   All automobiles sold in the United States since Jan. 1, 1968 have been equippped with a brake failure indicator, which illuminates a red light in view of the driver when a partial failure occurs in the brake system. There appears to be no data on the performance on this sensor; its reliability and effectiveness are totally unknown. A limited amount of data is available to suggest that public awareness that the device even exists is rather low.

3. The propensity of drivers to take correction action upon receipt of information.

   Example:

   Approximately 50% of all drivers whose bald tires were indicted as a cause for their accident indicated an awareness of their tread condition.

6.0 RECOMMENDATIONS

Consistent with the division of conclusions between sensor-specific technical judgments and critical conclusions regarding the data bases utilized in this study, these recommendations are of two basic types -- those which advance the technology of on-board vehicle sensors, and those which address the data base needs described in Section 5.2.

6.1 RECOMMENDATIONS FOR ADVANCEMENT OF SENSOR TECHNOLOGY

- Development and test of a brake performance sensor. This development program should utilize the results of this study and ongoing NHTSA program such as the Optimized Brake Inspection, Manual Brake and Static Brake programs to refine the performance requirements for a brake performance sensor and then proceed to preliminary development and test of a brake performance sensor capable of meeting these performance requirements.

- Although current concepts of tire underinflation warning systems do not show a favorable cost benefit ratio due largely to estimated maintenance and replacement costs, the potential for low cost systems exists. The development of a low cost effective system should be encouraged.

  To better understand this application, it is further recommended that studies be made of the effectiveness of tire inflation sensors through field tests using existing sensing systems. The in-use capabilities of tire inflation sensors should be determined by installation of several hundred sensors on vehicles of various types. These could be Government-owned vehicles, or privately owned cars. The sensors should be subjected to a full range of in-use environmental conditions, combined with the taking of data on how often sensor warnings were given and corrected by the vehicle operators. A program to conduct these tests might also be profitably combined with research into the existing tire inflation practices of the American motorist. The objective would be to answer questions relating to how and why surveys of tire inflation have shown a high incidence of underinflation.

- Conduct research into the feasibility of improved tread wear indicators. At issue here is whether improvements are possible without major changes in the manufacturing processes currently employed.

- It is recommended that the use of brake lining wear indicators be encouraged.

6.2 RECOMMENDATIONS FOR DATA BASE IMPROVEMENTS

As discussed in the section on conclusions, many of the data base deficiencies relate to all vehicle-in-use programs, rather than simply on-board sensors. In this context, there is a need for systems level analysis and specific, in-depth activities directed at specific research questions.

There has been a tendency toward specialization in VIU programs. For example, where once the entire topic of PMVI was subjected to analysis, one now finds separate programs directed at brake system visual inspection and brake test equipment. This is generally a healthy trend, reflecting an increasing depth of knowledge in these areas. However, the "big picture" associated with motor vehicle programs is also changing. The automobiles of today differ in significant ways from those of the late 1960's when some of the pioneering work in systems analysis of automotive safety problems were performed. Among the most important changes are the introduction of front disc brakes, and the general trend toward radial tires. In addition, the economics of inspection, accidents, and automobile maintenance have been continually changing.

To keep the "big picture" in focus, it is believed that it is necessary to update these studies, taking as the subject not one of the possible VIU countermeasures (PMVI, on-board sensors, vehicle design) but all of them at once.

A key area is the determination of consistent and reliable safety criticalities for all of the important subsystems of the automobile. The long-term solution to this problem is more accident investigation. It is believed that about 10,000 new accidents should be investigated to a level equivalent to that employed in Level C of the Indiana study, incorporating methodological improvements derived from the use of the existing data. Specifically, the accident sampling procedures should be refined to incorporate a representative national sample, and stratified to strengthen the data base in fatal and injury producing accidents. The analysis of each case should more carefully quantify the indictments made, rather than simply use the labels "certain", "probable", and "possible." The interface between field and laboratory studies should at all times be closely studied.

A reasonable goal for future accident investigations is the identification of specific failure modes contributing 0.1% or more to the national accident picture. A cut-off of 0.1% would correspond to accident causes costed at $.30 per year. This represents a plausible lower limit on problems that can be dealt with via vehicle-in-use or vehicle design countermeasures. The categorization of defects would be significantly more detailed than that presently employed in classifying the Indiana cases, which currently provides for classifying vehicle factors in 90 categories, 68 of which are bottom-tier categories (not further divided), and 22 of which represent aggregations of lower classifications. The manipulation of this data base would require automated techniques, developed from the manual screening procedures employed in this program, other similar programs (radar braking and anti-skid systems have also been analyzed using the Indiana data) and automated techniques currently available for manipulation of the HRSI data bank.

A sample size of 10,000 cases is suggested with a cut-off indictment totaling four or more cases. In a sample this size, one would expect to find 10 cases for each 0.1% contributor.

Assuming that defect involvement can be unambiguously determined, the probability that a 0.1% contributor would contribute 3 or less cases to a sample of 10,000 accidents is 0.01 and the probability that it will contribute no cases is 4.5×10^{-5}. As described in Section 2.2, the fact that defects appear at varying levels of certainty adds to the detection probability. Hence, a program of this type should provide an accurate snapshot of current problems in the VIU area.

The development of the needed safety criticality data using accident investigation will require many years -- 10,000 cases might be accumulated at 2,000 per year for 5 years. Until this is completed there is still no better data available than that used in this report. One possible improvement is the use of analytical techniques to develop interim estimates. Except for the activities reported under this program, this was last done in 1970 by Booz-Allen Applied Research, using techniques and sources of information markedly inferior to those available today. It is recommended that a new, broadly based analytical effort be undertaken to generate interim estimates.

In addition to the basic needs for safety criticality information, other unknowns in the behavioral area require resolution. The data base on owner knowledge of (and response to) simple sensors such as the brake failure indicator, high-beam indicator, alternator/generator light, and oil pressure warning light is presently very sketchy. This data could profitably be collected in conjunction with future vehicle condition surveys similar to those conducted under the NHTSA sponsored Motor Vehicle Inspection Evaluation Program (MVIEP).

Information on the motorist's awareness of vehicle condition is also essential. This data should continue to be collected in accident investigations and should also be incorporated in vehicle surveys.

Parts return programs and other repair industry programs should be exploited to characterize more fully the current repair practices of the American motorists.

If NHTSA must justify its programs against increasingly anti-regulatory attitudes in Congress and elsewhere, the collection of stronger data is a necessity.

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APPENDIX A

BIBLIOGRAPHY

APPENDIX A

BIBLIOGRAPHY

A.1 INTRODUCTION

A prime contributor to many aspects of the On-Board Vehicle Sensor Technology program is the relevant literature. All literature pertinent to the design and performance of the six vehicle subsystems, and to the sensor benefits and effectiveness considerations identified by the ten-criteria value-screening algorithm adopted for the study phase of the program has been sought. Since the literature forms an important base of data in the program, Avco has conducted an extensive search, acquisition and evaluation effort.

As a means of having some central control of the literature digestion process, a general bibliography for the On-Board Vehicle Sensor Technology program has been compiled, including all of the literature that has been actually collected and screened. Collection was done on the basis of the apparent relevance as suggested by the title. All of the available and acquired literature was brought to the attention of program contributors, through formal notification of acquisitions and their availability.

In the following sections of this Appendix, the results of the literature survey are presented. For convenience, frequently encountered abbreviations are shown in Table A-1. Agency and Publication sources are listed in Table A-2. These are followed by the alphabetical bibliography listing, and finally by a section describing the literature evaluation mechanics.

Table A-1

Abbreviations

FICAS	First International Congress on Automotive Safety - Sponsored by USDOT, National Motor Vehicle Safety Advisary Council (NMVSAC) on 17 - 19 July 1972 in San Francisco, California. Theme: Standardization of Automotive Diagnostic Systems.
USDOT	United States Department of Transportation
NHTSA	National Highway Transportation Safety Administration (DOT)
NHSB	National Highway Safety Bureau (DOT)
NMVSAC	National Motor Vehicle Safety Advisory Council (DOT)
IRPS	Institute for Research in Public Safety, Indiana University
HSRI	Highway Safety Research Institute, The University of Michigan
HSRC	Highway Safety Research Center, University of North Carolina

Table A-2

AGENCY AND PUBLICATION SOURCES

American Associations of Motor Vehicle Administrators

American Standards Institute

American Society of Mechanical Engineers

Arthur D. Little, Inc.

Automobile Club of Missouri

Automobile Club of South Cal.

Automobile Manufacturers Association

Automobile Safety Foundation

Bendix Corporation

Booz-Allen Applied Research, Inc.

California Institute of Technology

Champion Spark Plug

Chrysler Corp.

Clayton Manufacturing Company

Cornell Aero Lab/CALSPAN

Ford Motor Company

Frost and Sullivan, Inc.

Geophysics Corporation of America

General Electric Company

General Motors

Goodyear Tire & Rubber

Greening Associates

Hamilton Standard

Indiana, Union of, (IRPS)

Johns Hopkins University

Journal of Safety Research

Lockheed

Machine Design

Massachusetts Institute of Technology

Massachusetts, University of

Michigan, University of (HSRI)

Mitre Corporation

Motor Age

Motor Vehicle Manufacturing Association

Harvard University, School of Public Health (McFarland, et al)

National Academy Sciences

North Carolina, University of

North Carolina State University

Northern Research and Engineering (NOREC)

Northrop/Olson Laboratories

Olson Labs.

Operations Research, Inc.

RCA

Research/Development

Society of Automotive Engineers

Southwest Research Institute

Stanford Research Institute

Texas A&M University (TTI)

TRW Systems

United States Department of Transportation
- NHTSA
- NMVSAC
- TSC

United States Department of Health, Education, and Welfare EPA

Ultrasystems, Inc.

Wisconsin, University of

A.2 The Alphabetical Bibliography

The bibliography listing in this section has over 200 entries, representing documents which were obtained and screened for value to the On-Board Vehicle Sensor Technology program. It was found to be convenient for the purposes of this program to identify the source of the research for certain multi-volume documents, since only in this way could the totality of the published work on a program appear as one bibliographical entry. In some cases there were different authors among two or more volumes of the same report on the same program, and a bibliography constructed in the usual manner of alphabetical by last name of the author, or first mentioned author, would not be as meaningful for use. As a result, the work of researchers at various universities (Michigan, Indiana, Utah, North Carolina, etc.) will appear under an alphabetical entry for the university. The authorship of such documents is also noted where it was clear from the acquired document.

Also included in the alphabetical bibliography are the National Technical Information Service document numbers (PB numbers) associated with a specific document, where these numbers are known. As a result, both the Department of Transportation document number (DOT HS-XXX XXX) and the NTIS number (PB-XXXXXX) appear for many of the entries.

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A.3 LITERATURE EVALUATION MECHANICS

The primary objectives of the literature search have been to provide defendable evidence for asserting the possible value of sensing defective states in various components and subsystems of passenger cars, and establishing the state of the art in terms of current practice and known development trends. For these purposes, and to facilitate the reporting on the literature survey, a semi-formal procedure was adopted involving the execution of a literature evaluation form for documents of value to the program. Figure A-1 shows the form. Not every bibliography entry was evaluated in detail, but for each entry that was evaluated in detail a form was executed. The literature evaluation process is shown as an algorithm in Figure A-2.

As shown in the figure, each acquired document was subjected to a first level of review by a reading of the objectives and conclusions of the program being reported. If the document was determined to be relevant to the On-Board Vehicle Sensor program, it was skimmed to locate important information and the important information was thoroughly scanned. When a document was identified as vital to the program, a literature evaluation form was executed.

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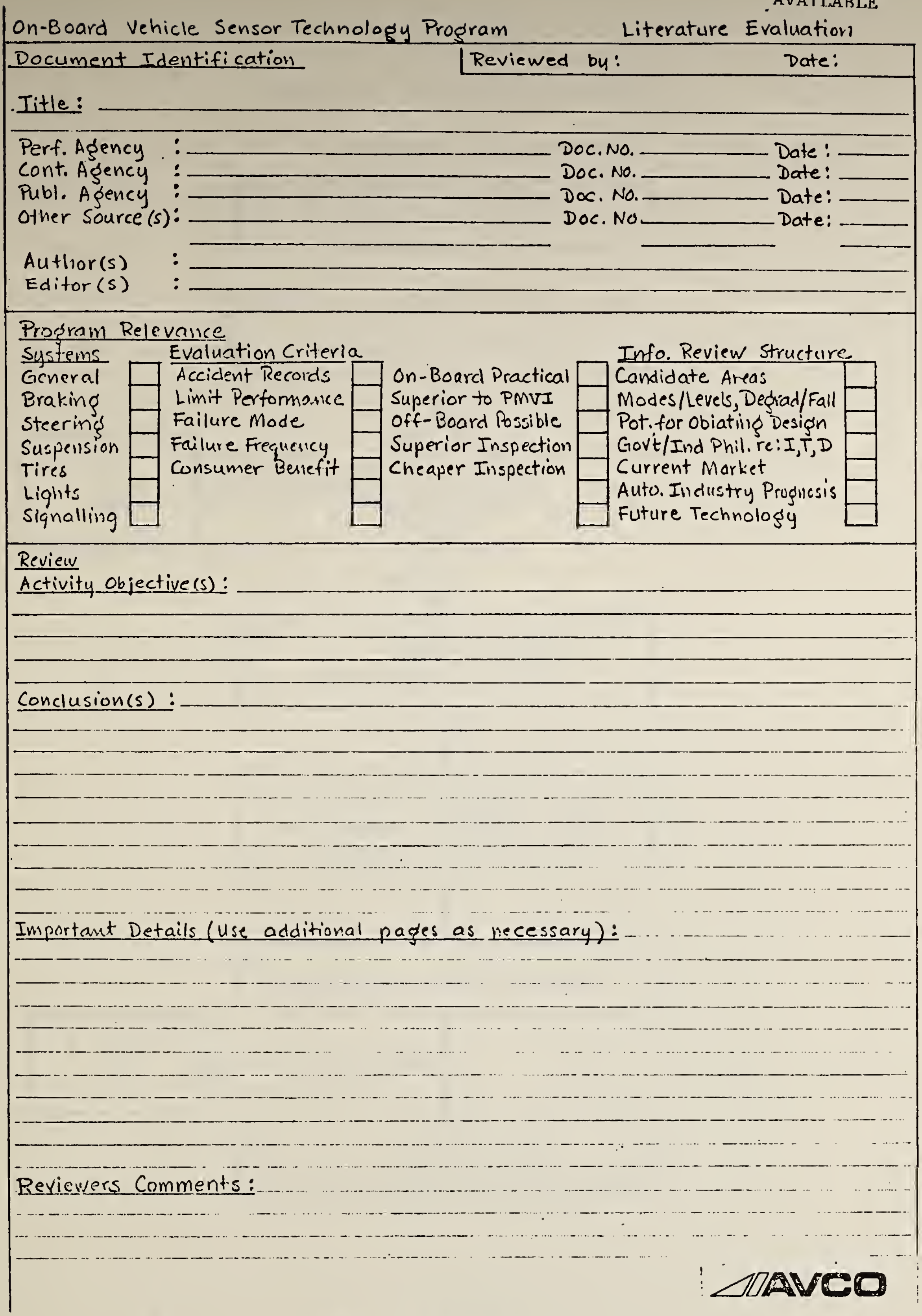


On-Board Vehicle Sensor Technology Program — Literature Evaluation

Document Identification

Reviewed by:

Date:

Title:

Perf. Agency: Doc. No. Date:
Cont. Agency: Doc. No. Date:
Publ. Agency: Doc. No. Date:
Other Source(s): Doc. No Date:

Author(s):
Editor(s):

Program Relevance

Systems
- General ☐
- Braking ☐
- Steering ☐
- Suspension ☐
- Tires ☐
- Lights ☐
- Signalling ☐

Evaluation Criteria
- Accident Records ☐
- Limit Performance ☐
- Failure Mode ☐
- Failure Frequency ☐
- Consumer Benefit ☐
- ☐
- ☐
- On-Board Practical ☐
- Superior to PMVI ☐
- Off-Board Possible ☐
- Superior Inspection ☐
- Cheaper Inspection ☐
- ☐
- ☐

Info. Review Structure
- Candidate Areas ☐
- Modes/Levels, Degrad/Fail ☐
- Pot. for Obiating Design ☐
- Gov't/Ind Phil. re: I,T,D ☐
- Current Market ☐
- Auto. Industry Prognosis ☐
- Future Technology ☐

Review
Activity Objective(s):

Conclusion(s):

Important Details (Use additional pages as necessary):

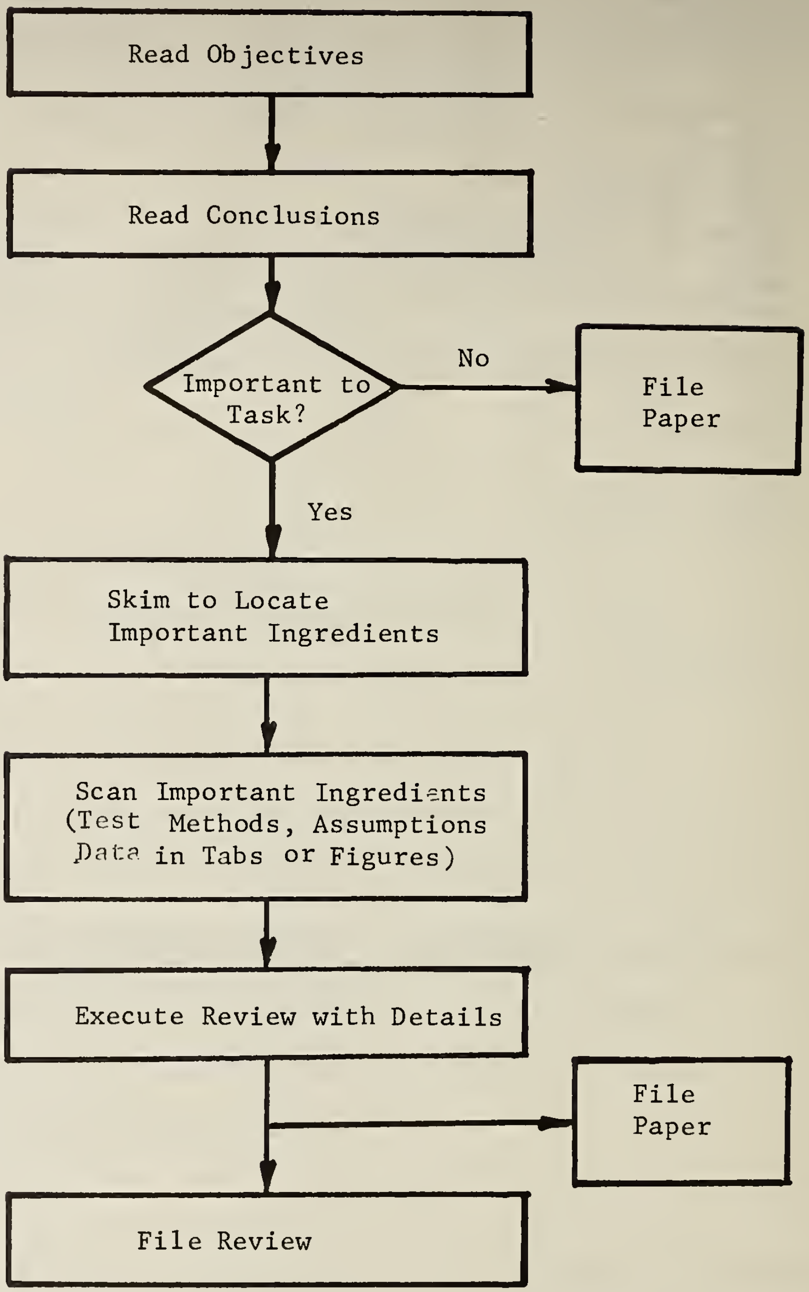
Reviewers Comments:

AVCO

Figure A-1 Literature Evaluation Form for the On-Board Vehicle Sensor Technology Program

Figure A-2

LITERATURE EVALUATION ALGORITHM


Read Objectives
Read Conclusions
Important to Task?
No
File Paper
Yes
Skim to Locate Important Ingredients
Scan Important Ingredients (Test Methods, Assumptions Data in Tabs or Figures)
Execute Review with Details
File Paper
File Review

The evaluation form is organized into three main sections, Document Identification, Program Relevance, and Review. In the section, Program Relevance, the content of the document is identified as having a bearing on the vehicle subsystems of interest, on one or more of the ten evaluation criteria tests, or having a contribution to one or more of the seven divisions for structuring the literature review described in the statement of work for this program. With this format, the cross-referencing of specific bibliography entries to the various categories of interest was systematically constructed.

APPENDIX B

U.S. PATENTS APPLICABLE TO BRAKE DEFECT SENSING

APPENDIX B

U.S. PATENTS APPLICABLE TO BRAKE DEFECT SENSING

The following U.S. patent synopses deal with methods of detecting brake system defects. These patents were reviewed as a part of the work performed under this contract as well as the Static Brake Program, Contract DDT-HS-4-00949.

This material was collected and used in the analyses of brake defect sensing.

LISTING OF U.S. PATENTS

ELECTRICAL

- Fluid Braking Apparatus
- Brake Indicating and Testing Device
- Brake Adjustment Indicating Device
- Brake Fluid Leak Detectors
- Brake Shoe Wear Indicator
- Vehicle Brake Condition and Operation Detecting System
- Brake Lining Wear Sensing Circuit
- Warning Device for Indicating Wear of Friction Pads in Disc Brake
- Worn Brake Indicator
- Brake Lining Wear Warning System
- Brake Wear and Adjustment Device

ACOUSTICAL

- Brake Alarm
- Brake Lining Wear Signalling Device
- Vehicle Brake Lining Wear Indicating Devices
- Wear Indicator For Brake Lining

ODOR

- Brake With Wear Detecting Means

VISUAL

- Brake Meter
- Brake Lining Wear Indicator

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PATENT SEARCH SYNOPSIS

PATENT DATE: Oct. 13, 1925

PATENT NUMBER: 1,557,330

TITLE: Fluid Braking Apparatus

INVENTOR: Joseph B. Reynolds, Croton Falls, New York

ASSIGNEE: - None -

TYPE - ELECTRICAL

SYNOPSIS:

The basic elements of a hydraulic braking system including master and wheel cylinders are described. In addition, the master cylinder has attached to it a four way distribution block with slave cylinder and an electrical warning switch for each wheel to indicate loss of fluid. In effect the fluid for each wheel is isolated from the master cylinder as a safety measure. The safety switches actuate a warning device, in this case, a Klaxon horn.

Avco Comment:

This appears to be the basis for hydraulic braking systems as we know them today.

SYNOPSIS DATE: 7/23/74

PREPARED BY: D. A. White

PATENT SEARCH SYNOPSIS

PATENT DATE: May 10, 1938

PATENT NUMBER: 2,117,027

TITLE: Brake Indicating and Testing Device

INVENTOR: Harold W. Langbein, Los Angeles, Calif.

ASSIGNEE: - None -

TYPE - ELECTRICAL

SYNOPSIS:

A system for monitoring brake equalization as a function of heating and displaying any difference on dashboard mounted millivoltmeters is described. Thermocouple sensors are mounted in the brake linings of left and right rear wheels and connected to a millivoltmeter with opposing voltages so as to null the meter. Likewise for the front wheels such that two meters describe the vehicle brake heating.

AVCO COMMENTS:

Similar to present day use of thermocouples for SAE tests on brake linings.

SYNOPSIS DATE: 7/22/74

PREPARED BY: D. A. White

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PATENT SEARCH SYNOPSIS

PATENT DATE: Dec. 5, 1939

PATENT NUMBER: 2,182,554

TITLE: Brake Adjustment Indicating Device

INVENTOR: Jean Baptiste Paul Henri Galle, Sceaux, France

ASSIGNEE: - None -

TYPE - ELECTRICAL

SYNOPSIS:

A system for monitoring differences in brake heating and displaying such difference on a dash board mounted galvanometer is described. A resistance thermometer is mounted in the backing plate of each wheel. These thermometers are tied into the four legs of a wheatstone bridge so as to indicate differences in braking effort by virtue of unequal heating causing the galvanometer to depart from null. Reference resistors and a switching means are also provided to isolate that wheel with abnormal heating.

AVCO COMMENTS:

Doubtful that a resistance thermometer in backing plate would be close enough to heat source for meaningful tracking of heat dissipation. Would expect considerable lag between heat generation and its indication on galvanometer.

SYNOPSIS DATE: 7/22/74

PREPARED BY: D. A. White

PATENT SEARCH SYNOPSIS

PATENT DATE: May 29, 1956

PATENT NUMBER: 2,748,378

TITLE: Brake Fluid Leak Detectors

INVENTOR: Joseph S. Feins, New York, N. Y.

ASSIGNEE: - None -

TYPE - ELECTRICAL

SYNOPSIS:

A secondary master cylinder reservoir with a means for warning of brake fluid loss is described. The reservoir contains a float mounted mercury switch which actuates a buzzer contained in a sealed cap of the reservoir. In addition, a transparent sight gage external to the reservoir provides visual indication of low fluid. Circuitry includes an ignition interlock.

Avco Comment:

This device precedes the introduction of dual master cylinders in automotive industry. In principle, it is similar to the brake fluid level (warning system used on 1974 Toyota Corona).

SYNOPSIS DATE: 7/23/74

PREPARED BY: D. A. White

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PATENT SEARCH SYNOPSIS

PATENT DATE: July 15, 1969

PATENT NUMBER: 3,456,236

TITLE: Brake Shoe Wear Indicator

INVENTOR: C. Labartino

ASSIGNEE:

TYPE - ELECTRICAL

SYNOPSIS:

This discloses an electrical alarm system which has as its key element conductors embedded in the brake shoe material at a depth corresponding to the replacement thickness of the brake linings. Alternate arrangements of circuits are included.

AVCO COMMENTS:

Scheme applies to any type of brake. Requires electrical interface. Does not require inspection or disassembly.

SYNOPSIS DATE: Aug. 26, 1976

PREPARED BY: M. Finigian

PATENT SEARCH SYNOPSIS

PATENT DATE: July 20, 1971

PATENT NUMBER: 3,594,721

TITLE: Vehicle Brake Condition and Operation Detecting System

INVENTOR: Ametz Frenkel, Lansdale; Michael R. Nakomechny, Valley Forge
Both of Pennsylvania

ASSIGNEE: Transducer Systems, Inc., Willow Grove, Pa.

TYPE - ELECTRICAL

SYNOPSIS:

A proximity type transducer with electrical output is mounted on the brake shoe. Used in conjunction with a switch on the brake pedal and associated circuitry it monitors:

a) Brake operation, in terms of brake shoe motion.

b) Brake condition, in terms of brake shoe motion from which lining wear is deduced.

Avco Comments:

It is doubtful that such a transducer would have sufficient sensitivity to develop a meaningful electrical output from disc brakes or well adjusted drum brakes because motion is so small.

SYNOPSIS DATE: 7/22/74

PREPARED BY: D. A. White

PATENT SEARCH SYNOPSIS

PATENT DATE: July 4, 1972

PATENT NUMBER: 3,675,197

TITLE: Brake Lining Wear Sensing Circuit

INVENTOR: Ronald W. Bennett, Miamisburg, Ohio:
Donald L. Parker, Middletown, Ohio;
Arthur R. Shaw, Dayton, Ohio

ASSIGNEE: General Motors Corporation, Detroit, Mich.

TYPE - ELECTRICAL

SYNOPSIS:

One lining/pad wear sensor suitable for disc or drum brakes and 3 sensing circuits are described. Features are:

a) Wire loop pad wear sensor attached to brake shoe with stamped metal clips. No modification of brake shoe or lining is required.

b) Sensing circuits are based on all wear sensors in series with indicator lamp and test switch. Modified circuits using relays or transistors to provide self test at ignition turn on are also presented.

AVCO COMMENTS:

Stamped clip for wire attachment is clever and inexpensive.

SYNOPSIS DATE: 7/24/74

PREPARED BY: D. A. White

PATENT SEARCH SYNOPSIS

PATENT DATE: Feb. 13, 1973

PATENT NUMBER: 3,716,113

TITLE: Warning Device for Indicating Wear of Friction Pads in Disk Brake

INVENTOR: Toyoaki Kobayashi, Naoji Sakakibara, Toshio Kondo, All of Kariya, Japan

ASSIGNEE: Aisin Seiki Kabushiki Kaisha, Kariya-Shi, Japan

TYPE - ELECTRICAL

SYNOPSIS:

Seven different pad wear detector designs are physically and functionally described. One electrical fail safe circuit for monitoring these detectors is also described. Features of this invention are:

a) Detector switches are operated, by movement of pad backing plate, by abrasively cutting a wire, or by release of prepositioned contacts when the pad wears down to the contact location.
b) The detection circuit (ground biased transistor) and each detector design is based on opening a circuit (as opposed to closing a circuit) by pad wear, such that any accidental open circuit in the system (other than brakes) would also indicate a failure. As such, it is designed to fail safe.
c) Each detector is spring loaded to lock in the open circuit position (failure indicato from excessive pad wear.
d) Circuitry consisting of transistors, resistors, and warning lamp are momentary activated at each ignition turn on as a self test feature.

AVCO COMMENT:

This patent contains well thought out design parameters which clearly included requirements for fail safe and self test features. It appears to be the basis for Toyota's Electro Sensor Panel (ESP) introduced on the 1974 Toyota Corona. The brake pad wear sensor (detector) actually used in the Toyota is a wire loop imbedded in the disk brake pad which is abraded to an open circuit when the pad thickness is worn down to .098 inch or less.

SYNOPSIS DATE 7/24/74

PREPARED BY: D. A. White

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PATENT SEARCH SYNOPSIS

PATENT DATE: Feb. 13, 1973

PATENT NUMBER: 3,716,831

TITLE: Worn Brake Indicator

INVENTOR: Jackie D. Rikard, 2529 N. Bell St., and Bobby G. Rikard, Rte 6,
Both of Kokomo, Ind.

ASSIGNEE: - None -

TYPE - ELECTRICAL

SYNOPSIS:

A disc or drum brake lining wear indicator based on a single electrical contact in each wheel/brake assembly, grounding out to the brake drum when lining is worn beyond limits. Features of this invention are:

a) Special boss on back of secondary brake shoe with a through hole and threaded adjustment with locknut to position grounding contact.

b) Replaceable grounding contact, suitably insulated from brake shoe.

AVCO COMMENT:

Special threaded boss on brake shoe does not appear practical. This appears to be a scheme by which the inventor modified one of his own vehicles.

SYNOPSIS DATE: 7/24/74

PREPARED BY: D. A. White

PATENT SEARCH SYNOPSIS

PATENT DATE: May 22, 1973

PATENT NUMBER: 3,735,343

TITLE: Brake Lining Wear Warning System

INVENTOR: Buddy F. Lane; Conald E. Church, Both of Richmond, Ind.

ASSIGNEE: Avco Corp., Richmond, Ind.

TYPE - ELECTRICAL

SYNOPSIS:

A drum brake lining wear indicator based on two contacts mounted (bonded) to the brake shoe and shorted out by the drum when lining is worn beyond limits. Similar contacts are described made from electrical wire crimped to anodized aluminum which in turn bonded to the brake shoe. Contact is made when the brake drum wears through the insulating anodize layer of the aluminum. Two readout circuits are described based on the use of biased SCR's to turn on one or four lamp type indicators and keep them lighted even though the detector contact is momentary when the worn brakes are applied. The only function of this device is to provide a warning of worn linings.

AVCO COMMENT:

Circuitry is interesting.

SYNOPSIS DATE: 7/24/74

PREPARED BY: D. A. White

PATENT SEARCH SYNOPSIS

PATENT DATE: Dec. 4, 1973

PATENT NUMBER: 3,776,329

TITLE: Brake Wear and Adjustment Device

INVENTOR: Frederick J. C. Hope, Chobham, Woking;
James M. Pigney, Bracknell - Both of England

ASSIGNEE: Self Energizing Disc Brakes Ltd., Datchet, Buckinghamshire,
England

TYPE - ELECTRICAL

SYNOPSIS:

This concept provides a drum brake adjustment mechanism located outside of each backing plate and mounted on the axle housing. It consists of linkages, brackets, cams, and insulating materials suitable to provide a mounting for reed switches, magnets, and movable magnetic shields (iron) to perform the following functions:

a) Provide manual adjustment point for each brake
b) Indicate excessive lining wear by removal of magnetic shield and actuation of a reed switch (and indicator lamp) when brakes are applied.
c) Indicate that brakes are out of adjustment by same reed switch technique.

AVCO COMMENT:

A very cumbersome kluge.

SYNOPSIS DATE: 7/24/74

PREPARED BY: D. A. White

PATENT SEARCH SYNOPSIS

PATENT DATE: August 10, 1965

PATENT NUMBER: 3,199,631

TITLE: Brake Alarm

INVENTOR: W. J. Blankemeyer

ASSIGNEE:

TYPE - ACOUSTICAL

SYNOPSIS:

Proposes and claims the idea that a cantilever spring finger can be fixed to a brake shoe such that at a predetermined wear point, the finger contacts a serrated track in the brake drum, thus producing an audible signal.

AVCO COMMENTS:

Applies to lining wear (although sensitive to drum wear), does not require disassembly or inspection. No electrical interface is required. Could apply to disc brakes, but not covered in this patent.

SYNOPSIS DATE: Aug. 26, 1976

PREPARED BY: M. Finigian

PATENT SEARCH SYNOPSIS

PATENT DATE: October 29, 1968

PATENT NUMBER: 3,407,906

TITLE: Brake Lining Wear Signalling Device

INVENTOR: H. H. Lorenz

ASSIGNEE:

TYPE - ACOUSTICAL

SYNOPSIS:

Proposes spring loaded clapper which is restrained by an erodible pin which releases the clapper when brake lining wear has progressed to a predetermined level. This produces an audible signal.

AVCO COMMENTS:

Applies to drum brake linings only, does not require disassembly or inspection. No electrical interface is required.

SYNOPSIS DATE: Aug. 26, 1976

PREPARED BY: M. Finigian

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PATENT SEARCH SYNOPSIS

PATENT DATE: May 28, 1968

PATENT NUMBER: 3,385,256

TITLE: Vehicle Brake Lining Wear Indicating Devices

INVENTOR: L. M. Forbush

ASSIGNEE:

TYPE - ACOUSTICAL

SYNOPSIS:

This disclosure describes vehicle brake lining wear indicating devices wherein the occurrence of sufficient lining wear releases a resilient member from an inoperative position so that it can assume an operative position and provide an audible signal to the vehicle operator.

AVCO COMMENTS:

Applies to drum brake linings only, does not require disassembly or inspection. No electrical interface is required.

SYNOPSIS DATE: Aug. 26, 1976

PREPARED BY: M. Finigian

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D124

PATENT SEARCH SYNOPSIS

PATENT DATE:

PATENT NUMBER: Patent Specification

TITLE: Wear Indicator For Brake Lining

INVENTOR: Richard Kennel

ASSIGNEE:

TYPE - ACOUSTICAL

SYNOPSIS:

Proposes a flat spring which is restrained in curled configuration by a rivet type fastener. The material and location of head of this fastener are such that when the linings need replacement, the head is worn thru, thus releasing one end of the spring to rub on the brake drum. This produces an audible signal.

AVCO COMMENTS:

Device applies to drum brakes only. Requires no electrical interface. Does not require disassembly or inspection.

SYNOPSIS DATE: Aug. 26, 1976

PREPARED BY: M. Finigian

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PATENT SEARCH SYNOPSIS

PATENT DATE: February 13, 1962

PATENT NUMBER: 3,020,873

TITLE: Brake With Wear Detecting Means

INVENTOR: J. E. Bodkin

ASSIGNEE:

TYPE - ODOR

SYNOPSIS:

Proposes the idea that a pellet can be embedded in a brake lining which is made from material which produces a stink when heated. If the wear proceeds to the point where one or more of these pellets is exposed, the driver is allerted by his olfactory sense.

AVCO COMMENTS:

Applies to lining and pad wear indicators. Does not require disassembly or inspection. No electrical interface is required.

SYNOPSIS DATE: Aug. 26, 1976

PREPARED BY: M. Finigian

PATENT SEARCH SYNOPSIS

PATENT DATE: Nov. 6, 1928

PATENT NUMBER: 1,690,121

TITLE: Brake Meter

INVENTOR: August Klimek, Chicago, Ill.

ASSIGNEE: - None -

TYPE - VISUAL

SYNOPSIS:

A remote hydraulic sight gage type indicator for an external contracting mechanical brake is described. Four such devices are suggested, one for each wheel of an automobile.

AVCO COMMENTS:

Archaic.

SYNOPSIS DATE: 7/22/74

PREPARED BY: D. A. White

PATENT SEARCH SYNOPSIS

PATENT DATE: May 16, 1972

PATENT NUMBER: 3,662,863

TITLE: Brake Lining Wear Indicator

INVENTOR: Edward K. Dombeck

ASSIGNEE:

TYPE - VISUAL

SYNOPSIS:

Proposes the idea that a conical plug of marking material may be embedded (or installed) in a disc pad so that when wear has progressed to the point where replacement is advisable, a visible track is left on the disc. This track is not destructive and, by making the marker conical in shape, will become wider as the wear progresses further. This method does not require disassembly but does require inspection.

Also proposes an audible wear indicator for disc pads wherein a weight on a flexible tether is released at a predetermined wear point. The weight pouncing on the rotary wheel gives audible warning. This method does not require disassembly or inspection.

AVCO COMMENTS:

Applies to disc pads only. No electrical interface is required.

SYNOPSIS DATE: Aug. 26, 1976

PREPARED BY: M. Firigian

APPENDIX C

ANALYSES AND EVALUATION

APPENDIX C

ANALYSES AND EVALUATION

A limited structural analysis and evaluation has been performed to assess the probable strain levels that can be measured in key components of typical drum and disc brake assemblies. The results of the analysis are provided in this appendix.

In keeping with the intent of the evaluation, the assessment contained herein reflects an effort that is consistent with obtaining a coarse estimate, only, of the probable levels of strain for two brake configurations randomly selected from hardware that was available. The drum brake evaluation is contained on pages C-1 through C-6, and the disc brake evaluation on pages C-7 through C-14.

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PARA. NO.	1	TITLE: DRUM BRAKE INSTRUMENTATION EVALUATION	ANAL. BY	
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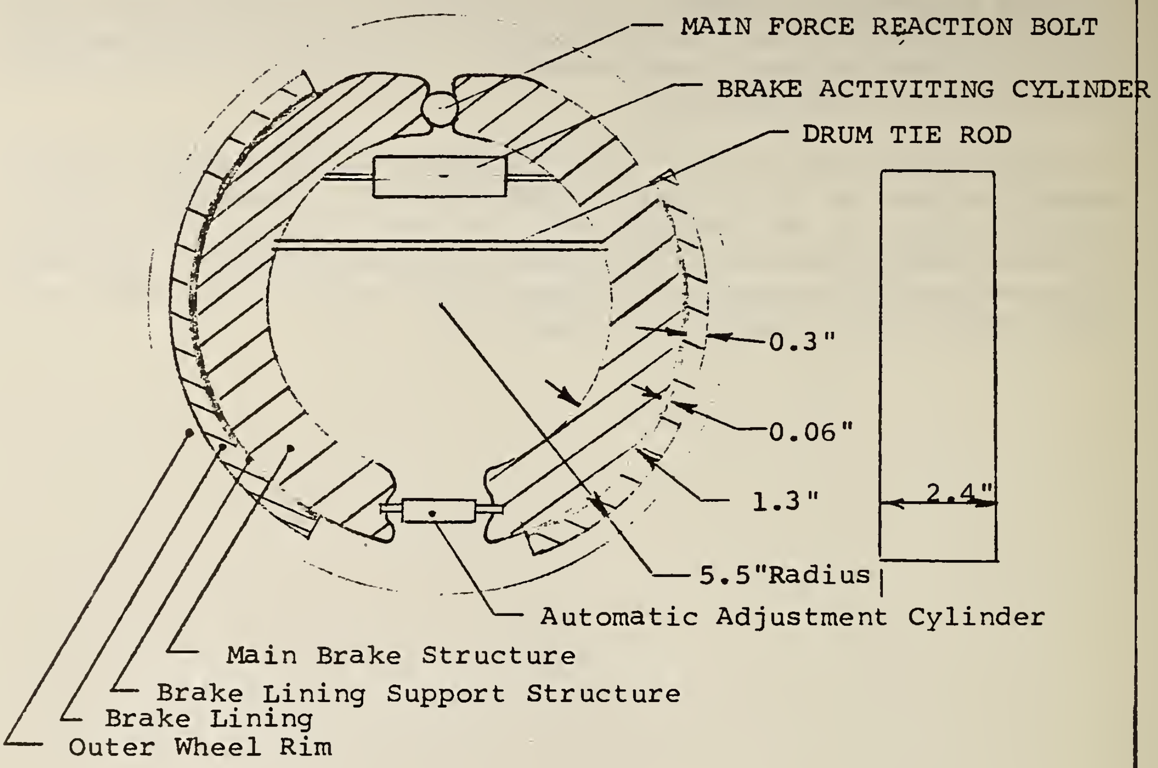
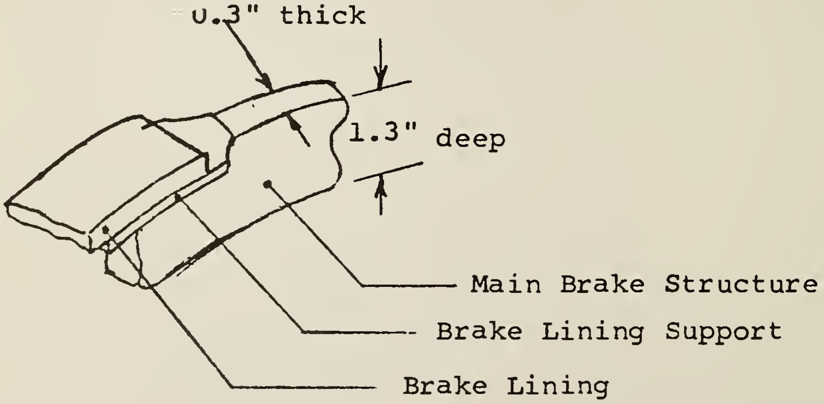
SCHEMATIC OF BRAKE MECHANISM



SCHEMATIC OF MAIN BRAKE STRUCTURE NEAR REACTION BOLT



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PARA. NO.	2	TITLE: DRUM BRAKE INSTRUMENTATION EVALUATION	ANAL. BY	
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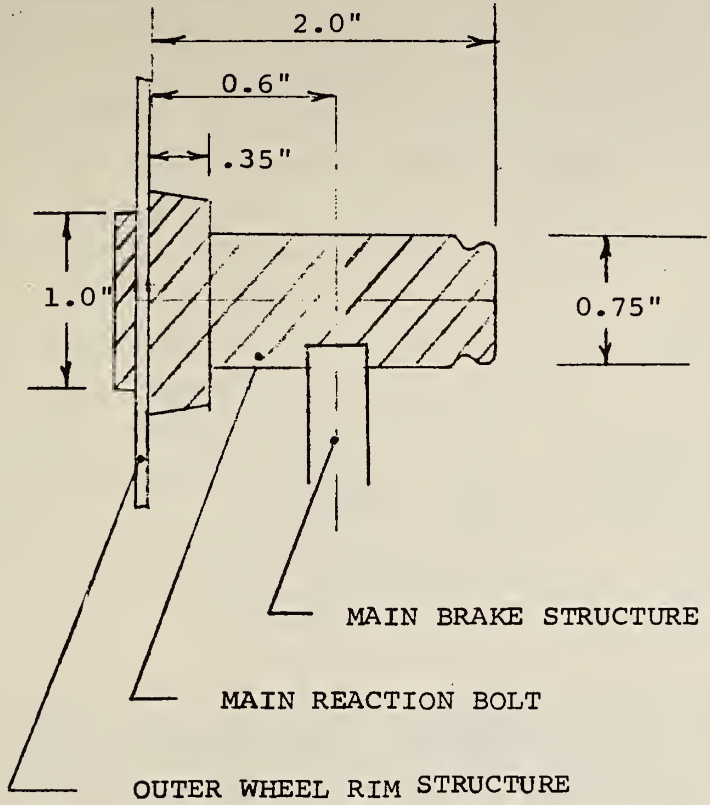
SCHEMATIC OF MAIN REACTION BOLT



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PARA. NO.	3	TITLE: DRUM BRAKE INSTRUMENTATION EVALUATION	ANAL. BY	
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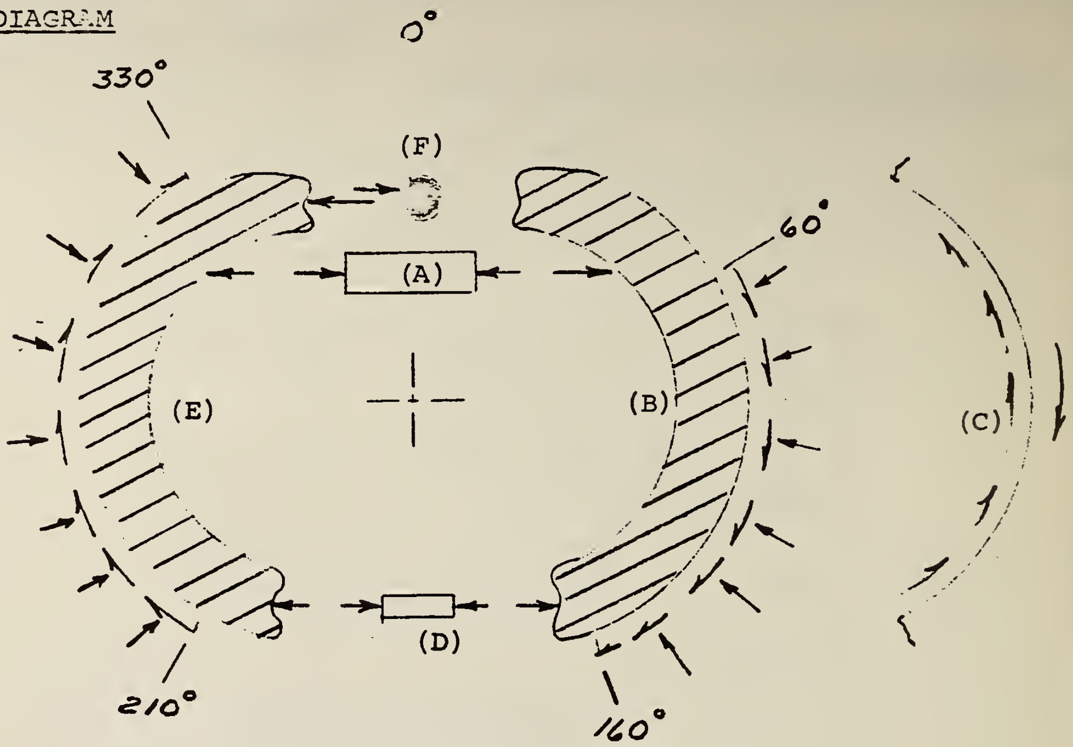
LOADS DIAGRAM



The brake mechanism is initiated by the hydraulic cylinder (A) which forces the two brake linings (B) and (E) out radially into contact with the rotating wheel drum (C). The location of the brake lining (B) from 60° to 160° creates a force distribution of normal loads and tangential friction loads (that are a result of the lining coefficient of friction) which cause the entire structure of (B) to drive against the mechanism (D). The brake assembly (E) thus reacts the loading from (D) and its own loads from bearing against the outer wheel rim through the single externally retained structure of bolt (F). The cylinder (A) does provide a load redundancy as far as its force level is possible.

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PARA. NO.	4	TITLE:	ANAL. BY	
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THE BALANCE OF FORCES CAN BE CALCULATED WITH THE COEFFICIENT OF FRICTION AND APPLIED CYLINDER (A) LOADS KNOWN. HOWEVER FOR A POSTULATED "G" LOADING OF THE ENTIRE BODY DURING BRAKING THE MAXIMUM FORCES IN THE MAIN REACTION BOLT AND MAIN BRAKE STRUCTURE NEAR THIS BOLT ARE KNOWN.

THAT IS, IF A PANIC STOP PROVIDES A "1G" BRAKING DECELERATION ON A 4000 # VEHICLE THEN MAXIMUM BRAKE LOADS (QUASI-STATIC) ARE FOR EACH WHEEL:

$$F_x = \frac{4000 \times 1G}{4} \approx 1000\ \#_{\text{FORCE}}$$

THE MEASUREABLE STRAIN IN THE BRAKE STRUCTURE IS

$$\epsilon = \frac{F_x}{AE}$$

WHERE $A =$ CROSS SECTIONAL AREA OF STRUCTURE

$E =$ YOUNG'S MODULUS OF BRAKE STRUCTURE

$$\epsilon = \frac{1000}{1.3(.3)(29)10^6}$$ (ASSUMING STEEL)

$= .000088$ IN/IN (COMPRESSION)

AND A STRESS OF

$$\sigma = \epsilon E = 2564 \text{ PSI}$$ (COMPRESSION)

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PARA. NO.	5	TITLE: DRUM BRAKE INSTRUMENTATION EVALUATION	ANAL. BY	
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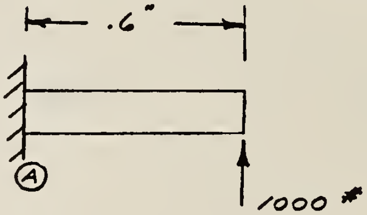
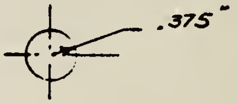
BOTH THE VALUES OF STRAIN AND STRESS ARE SMALL WHICH IS FAVORABLE FOR LARGE STRUCTURAL SAFETY MARGINS BUT UNFAVORABLE FOR MEASUREMENT OF LOADS WITH GOOD ACCURACY. REDUCTION OF CROSS-SECTION WOULD PROVIDE A TRADE-OFF BETWEEN SAFETY FACTOR AND MEASUREMENT CAPABILITY BUT CONSIDERATION OF THE SYSTEM STIFFNESS WOULD HAVE TO BE INCLUDED AT SOME POINT.

A SECOND ELEMENT IN THE DESIGN WHICH PROVIDES A DIRECT LOAD-FORCE REACTION OF THE BRAKING SYSTEM IS THE MAIN REACTION BOLT. THE STRAIN IN THIS STRUCTURAL ELEMENT CAN BE ESTIMATED BY APPROXIMATION AS A BEAM ELEMENT'





STRESS AT Ⓐ

$$\sigma = \frac{Mc}{I} = \frac{1000(.6)(.375)(4)}{\pi\,(.375)^4} = 14487$$

$$\epsilon = \frac{\sigma}{E} = \frac{14487}{29\times10^6} = .0005 \text{ IN/IN}$$

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PARA. NO.	6	TITLE: DRUM BRAKE INSTRUMENTATION EVALUATION	ANAL. BY	
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THIS VALUE OF ESTIMATED STRAIN IS A MAXIMUM VALUE SINCE, FOR THESE DIMENSIONS, THE BOLT DOES NOT BEHAVE AS AN IDEAL BEAM BUT REACTS THE APPLIED LOAD WITH A CONSIDERABLE MAGNITUDE OF SHEAR. AGAIN, REDUCTION OF THE BOLT WALL THICKNESS BY INTRODUCING A HOLLOW BOLT WOULD CONSTITUTE A SAFETY FACTOR VS STRAIN MEASUREMENT TRADE OFF.

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PARA. NO.	7	TITLE: DISC BRAKE EVALUATION	ANAL. BY	
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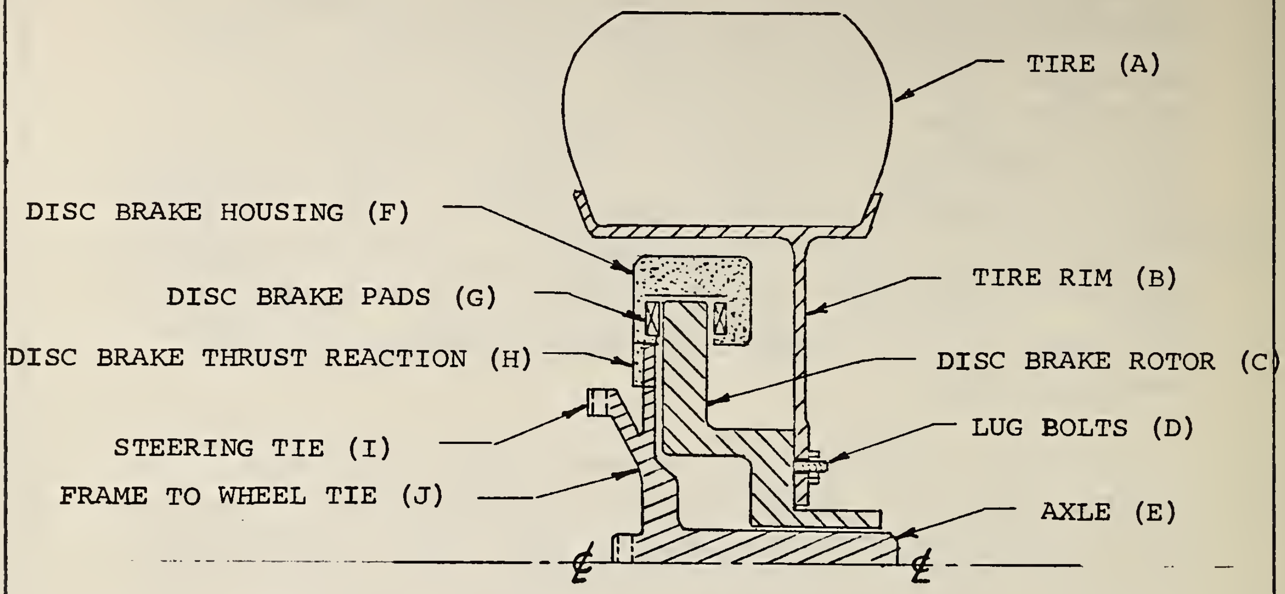
WHEEL SCHEMATIC WITH DISC BRAKE MECHANISM



In the Disc Brake mechanism the braking action is effected by the compression of a rotor between facing brake pads. The tire(A) and tire rim (B) are secured to a central Disc Brake Rotor (C) by Lug Bolts (D). This entire assembly rotates about the wheel Axle (E) which is stationary. The axle forms part of the wheel frame (J) that structurally ties the wheel assembly to the car frame. Part of this assembly provides the mechanism for steering in the Steering Tie (I). When the brakesare initiated the Disc Brake Pads (G) bear against the Rotor (C) and through friction slow the rotation of the rotor, tire rim and tire. The Disc Brake Housing (F) attempts to rotate under the frictional loads but is restrained by the bearing of the Thrust Reaction (H) into the Wheel frame (J). This bearing location, in direct reaction to the braking force, is the primary location for measuring the effective braking loads.

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PARA. NO.	8	TITLE:	ANAL. BY	
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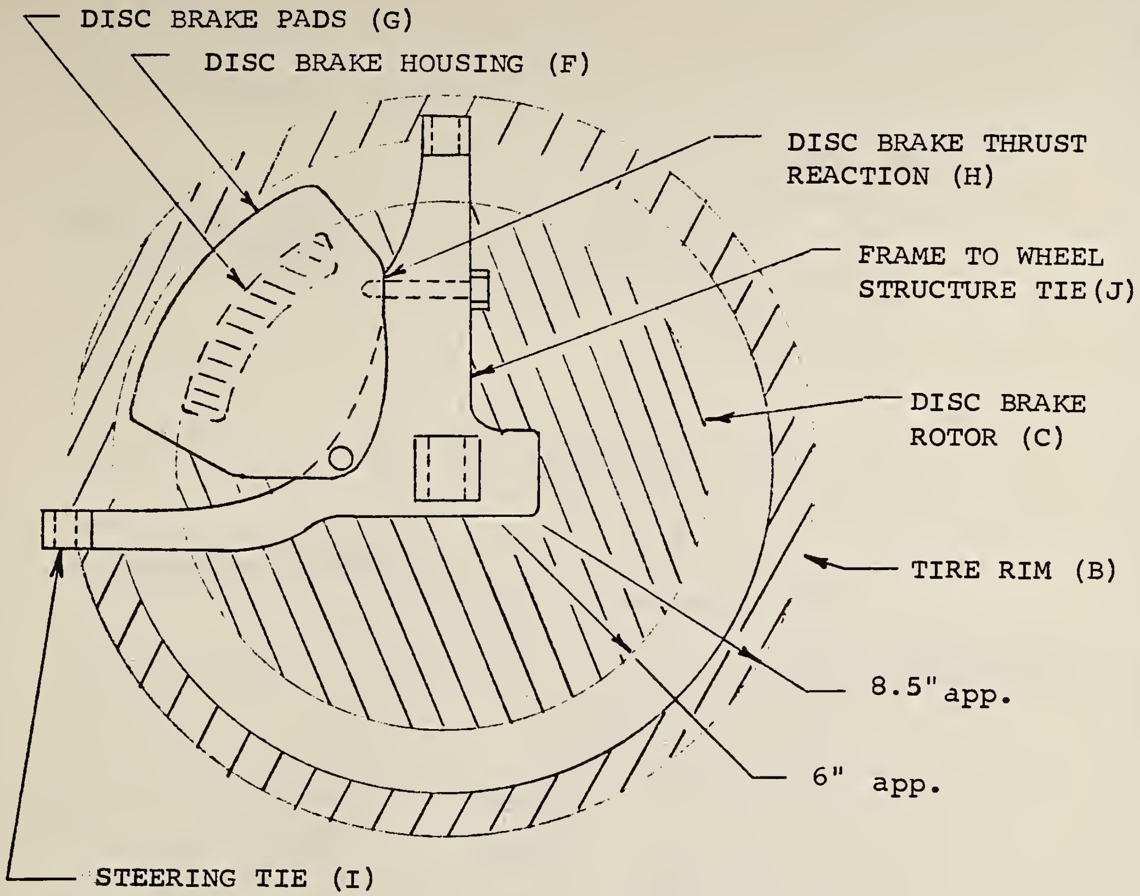
INTERIOR VIEW OF WHEEL AND BRAKE ASSEMBLY



This view describes pictorially the relationship of the rotor, brake pads and brake housing, and the structural wheel frame tie to the main vehicle frame. The disc brake housing can be seen to be attached to the wheel frame by a bolt about which it rotates and the horizontal bolt which maintains the attachment to react the primary brake thrust loads.

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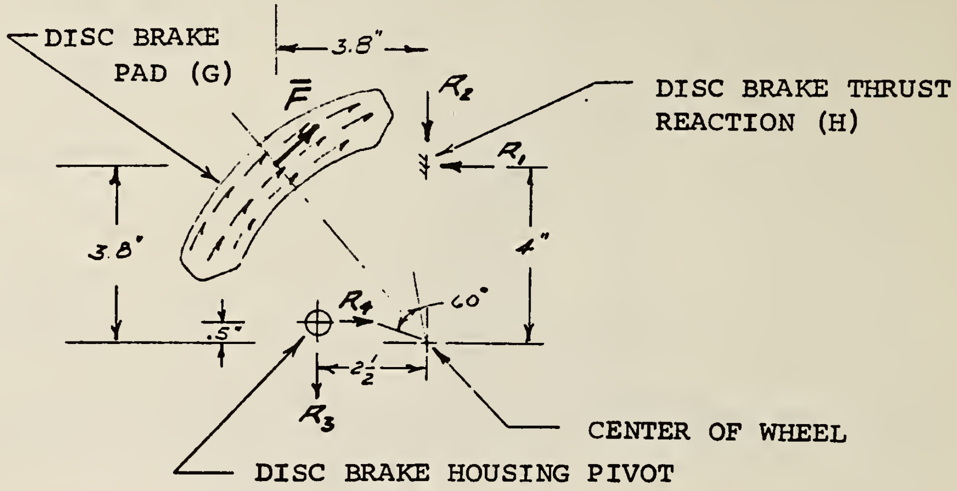
LOAD REACTION SCHEMATIC



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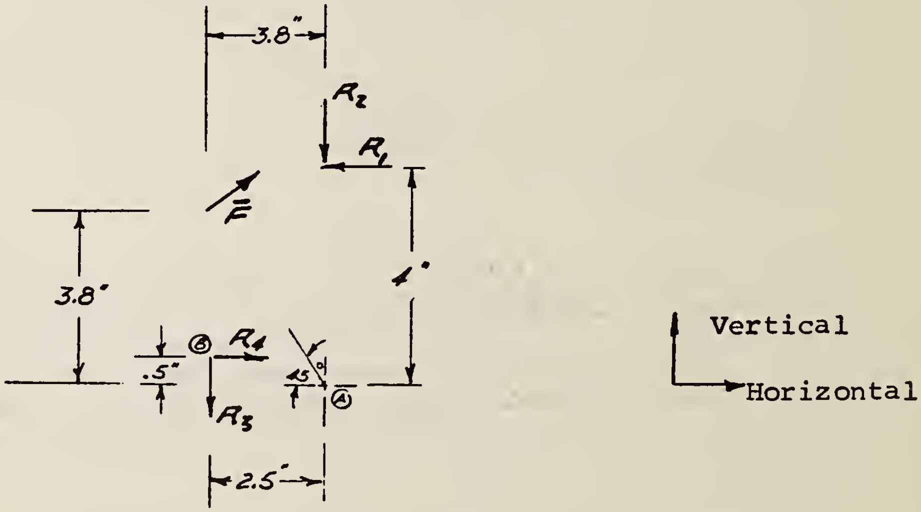

Note that the summation of friction forces on the brake pads must integrate to an equivalent force acting tangent to the center of radius of the brake pad, which is formed as a section of an arc. The acting force is centered at the median point for the arc section and tangent to the arc struck for the disc pad.

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MOMENT AND FORCE SUMMATIONS

1. $\Sigma F_H = 0$

$$R_4 + \bar{F}\cos 45^\circ - R_1 = 0$$

2. $\Sigma F_V = 0$

$$R_2 + R_3 - \bar{F}\cos 45^\circ = 0$$

3. $\Sigma M_A = 0$

$$4R_1 + 2.5R_3 - .5R_4 - \bar{F}(3.8)/\cos 45^\circ = 0$$

4. $\Sigma M_B = 0$

$$3.5R_1 - 2.5R_2 - 1.3\bar{F}\sin 45^\circ - 3.3\bar{F}\cos 45^\circ = 0$$

$$R_4 = R_1 - \bar{F}(.707) \qquad (Eq\ 1)$$

$$R_3 = -R_2 + \bar{F}(.707) \qquad (Eq\ 2)$$

(Eq 3) $4R_1 - 2.5R_2 + 2.5\bar{F}(.707) - .5R_1 + .5\bar{F}(.707) - 3.8\bar{F}/.707 = 0$

(Eq 4) $3.5R_1 - 2.5R_2 - 4.6\bar{F}(.707)$

$$3.5R_1 - 2.5R_2 - 4.6\bar{F}(.707) = 0 \qquad (Eq\ 5)$$

IF ONE IGNORES THE RELATIVE STIFFNESSES AND ASSEMBLY TORQUES OF THE PIVOT AND THRUST REACTION BOLT, THE DESIGN WOULD APPEAR TO HAVE REDUNDANT LOAD PATHS.

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PARA. NO.	11	TITLE:	ANAL. BY	
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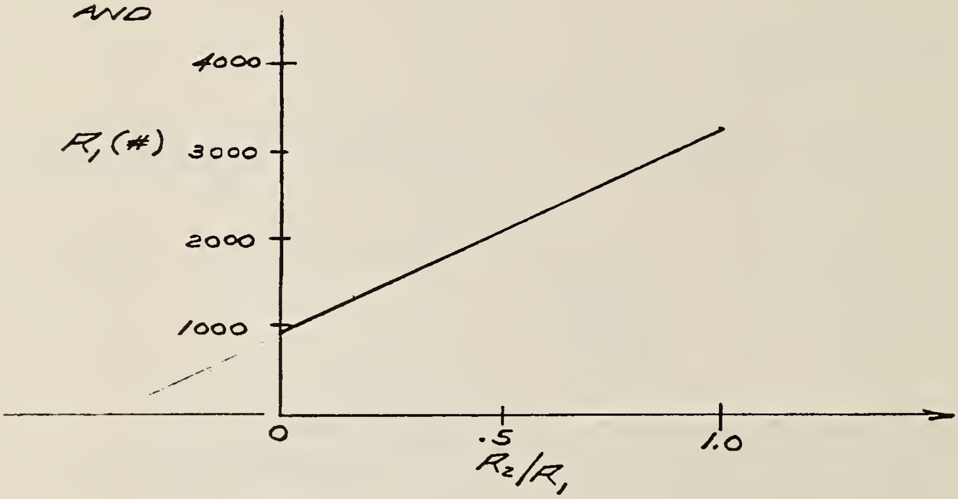
HOWEVER, BY DESIGN INSPECTION THE REACTION R_2 MUST BE SMALL COMPARED TO ALL OTHER LOADS AND REACTION. THE SENSITIVITY OF R_1 TO THIS ASSUMPTION CAN BE ILLUSTRATED NONETHELESS.

SINCE IT WAS PREVIOUSLY SHOWN THAT, IN A PANIC STOP, WHEEL BRAKING FORCES ARE TYPICALLY ON THE ORDER OF 1000 # THEN EQUATION 5 IS

$$3.5R_1 - 2.5R_2 = 3250\ \#$$

AND



NOTE THAT, BY DESIGN, R_2 WOULD NOT APPEAR TO BE CAPABLE OF BEING NEGATIVE. IF IT WERE R_1 COULD THEN THEORETICALLY BECOME ZERO AND THIS IS NOT REASONABLE UPON EXAMINATION OF THE BASIC DESIGN APPROACH.

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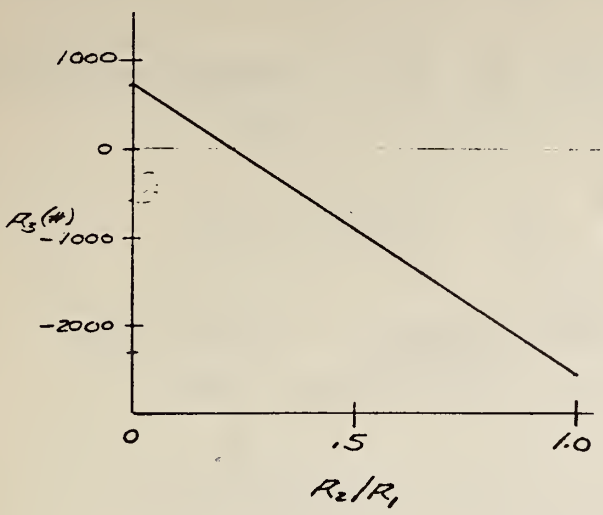
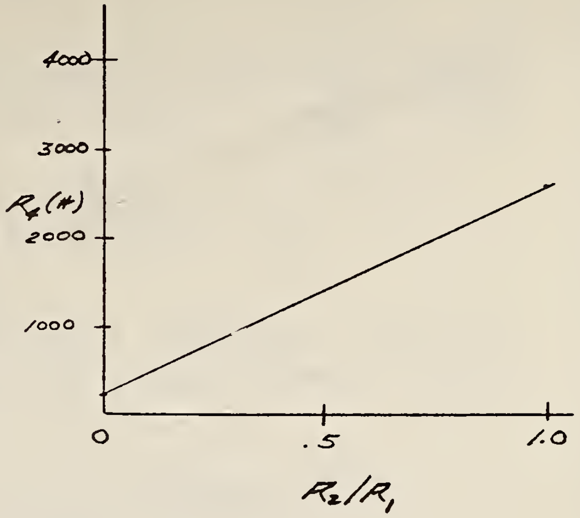
AND

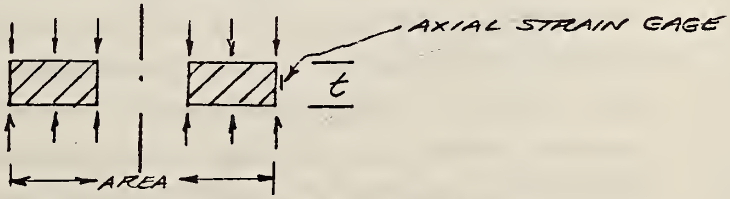




THUS MINIMUM LOADS IN THE SYSTEM RESULT IF R_2 IS LIMITED TO SMALL REACTION LOADS AND A MINIMUM VALUE OF R_1 IS OBSERVED TO BE ON THE ORDER OF 925 #

THIS LOAD MAY WELL BE MONITORED BY A FORCE TRANSDUCER IN THE FORM OF A WASHER APPROPRIATELY STRAIN GAGED TO MEASURE COMPRESSIVE LOADS AND LOCATED AT THE THRUST REACTION BOLT (H)

$\int p = F$



WHERE t IS ARBITRARY AND $\epsilon = f(\text{AREA})$

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PARA. NO.	13	TITLE: DISC BRAKE EVALUATION	ANAL. BY	
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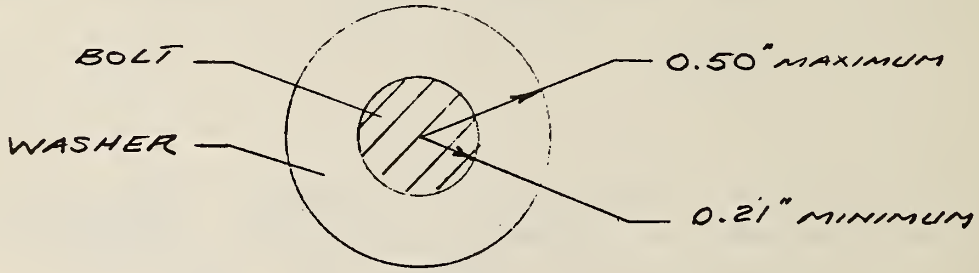
THUS

$$\sigma_c = \frac{\bar{F}}{A} \quad \text{OR} \quad \epsilon_c = \frac{\bar{F}}{AE}$$

FOR MINIMUM VALUE OF R, AND PANIC 1G STOP;
FOR STEEL WASHER OF $E = 30 \times 10^6$ PSI

$$\epsilon = \frac{925^{\#}}{30 \times 10^6} \ \frac{1}{A} = \frac{31 \times 10^{-6}}{A} \ \text{IN/IN}$$

TYPICAL WASHER FOR AVAILABLE AREA OF THRUST REACTION FLANGE DESIGN IS:



$$\text{MAXIMUM AREA} = \pi(.5^2 - .21^2) = .647 \ \text{IN}^2$$

$$\epsilon_{MIN} = \frac{31 \times 10^{-6}}{.647} = 48 \ \text{MICROINCHES/INCH}$$

CORRESPONDING TO: 1500 PSI

THUS, IN A NON-PANIC STOP OF .1G, RATHER THAN 1G, MEASURED WASHER STRAINS DUE TO BRAKING WOULD BE ON THE ORDER OF 5 MICROINCH/INCH, ASSUMING A COMPLETE STEEL WASHER. THE STRAIN MAGNITUDES COULD BE READILY INCREASED BY REDUCING WASHER SIZE AND ALLOWING HIGHER STRESSES OR USING OTHER MATERIALS.

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PARA. NO.	14	TITLE: DISC BRAKE EVALUATION	ANAL. BY	
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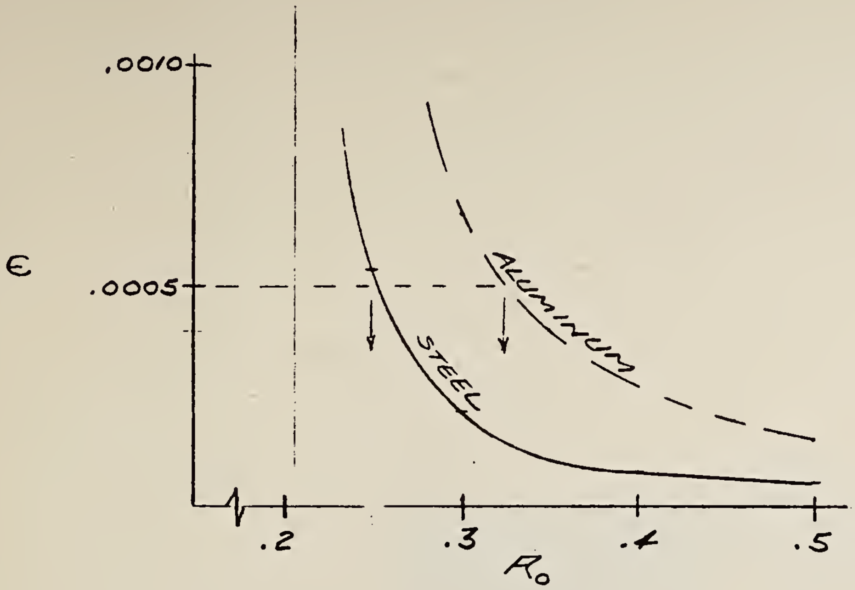
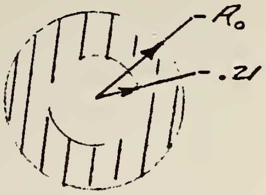
THE RELATIONSHIP BETWEEN WASHER SIZE AND STRAIN CAN BE SEEN BY:





AS CAN BE SEEN STRAIN MAGNITUDES IN THE WASHER OF 500 MICROSTRAIN CAN BE REALIZED EITHER BY USING AN ALUMINUM WASHER OF OUTSIDE RADIUS OF .32" (5000 PSI STRESS) OR A STEEL WASHER OF .24" (15000 PSI). THE STEEL WASHER WIDTH OF ONLY .030" INCH WOULD APPEAR UNREASONABLE. THE USE OF THE ALUMINUM WASHER APPEARS PRACTICAL AND PROVIDES STRAINS OF THE SAME MAGNITUDE AS COMPUTED FOR THE DRUM BRAKE, I.E. 50×10^{-6} IN/IN FOR A 0.1G NORMAL STOP.

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